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REPORT NO. 20

DRILLING OF TITANIUM AND ITS ALLOYS

Project M993

by

W. W. GILBERT
P. R. VISSER

July, 1953

U. S. ARMY, ORDNANCE CORPS
CONTRACT NO. DA-20-018-ORD-11918

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ENGINEERING RESEARCH INSTITUTE
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REPORT NO. 20

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Production Engineering Department

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SUMMARY SHEET

I. Engineering Research Institute, University of Michigan, Ann Arbor, Michigan

II. U. S. Army, Ordnance Corps.

III. Project No. TB4-15
Contract DA-20-018 ORD-11918, RAD No. ORDTB-1-12045.

IV. Report No. WAL 401/109-20

V. Priority No. - None

VI. Investigation of machinability of titanium-base alloys.

VII. Object:

The object is to obtain force and tool-life data on drilling titanium and its alloys, and to ascertain the best drill design and cutting practice.

VIII. Summary:

Various drilling conditions and drill designs were tested on four grades of titanium. Torque, thrust and drill-life characteristics were investigated. The effect of cutting fluids was also tested.

IX. Conclusions:

1. High helix angles reduce torque and thrust.
2. Drill stiffness is of great importance.
3. A highly chlorinated and sulfurized mineral oil performs best as a cutting fluid in reducing torque and thrust.
4. Cutting speeds of 70 fpm for Ti-75A and 30 fpm for titanium alloys are recommended.

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DRILLING OF TITANIUM AND ITS ALLOYS

OBJECT

The object of this series of tests was to determine the torque, thrust, power, and unit-horsepower variations as affected by speed, feed, drill diameter, drill design, and cutting fluids when drilling several grades of titanium and SAE 1045 steel.

At the same time, observations were made of general drill performance. Such factors as chip formation, drill vibration, surface finish, and cause of failure were closely observed. The data gathered from these tests made it possible to select certain operating conditions as best for drilling titanium and its alloys.

TEST PROCEDURE

Various sets of tests were run on all titanium alloys, commercially pure titanium, and SAE 1045 steel. Torque and thrust, as affected by drill diameter, feed, and speed, were investigated during the first series of tests. At first the cutting speed of the drills was kept constant and the feeds varied. Later the feed was kept constant and the cutting speed was varied. For the tests in which the cutting speed was kept constant, that speed of revolution of the drill press was selected which gave a cutting speed of approximately 25 fpm for the various drill sizes.

The drills used in this series of tests were a standard HSS jobber drills with an oxide surface treatment, marketed by the National Twist Drill and Tool Company of Rochester, Michigan. The drills had diameters of 1/4, 3/8, 1/2, and 1 inch. The feeds used were 0.004, 0.006, 0.009, 0.014, and 0.021 inches per revolution. (The two higher feeds were only used on the 1/2 inch and 1 inch drills.) The cutting speeds were 12, 25, 50, and 100 fpm (standard speeds on the drill press were chosen to approximate the desired fpm values.) The work material was clamped in a vise which was mounted directly on the dynamometer. The dynamometer deflections due to torque and thrust were recorded on a Sanborn Twin-Viso recorder during the drilling of a one-inch-deep hole.

The second series of tests investigated the torque and thrust as affected by drill design and operating conditions. During these tests, the cutting speed was kept constant at 22.1 feet per minute. Three feeds of 0.004, 0.006, and 0.009 inch per revolution were used. All the drills tested were standard 3/8 inch-commercially ground drills unless specified otherwise.

The variables in drill design which were checked were as follows:

1. Helix angle

   a. straight flute (0°)
   b. low spiral (18°)
   c. standard (30°)
   d. high spiral (40°)

2. Drill stiffness

   a. long length (auto long)
   b. medium length (auto short)
   c. standard
   d. short (stub screwmachine)
   e. heavy duty (extra thick web)

3. Drill material

   a. high-speed steel (standard drill)
   b. carbon tool steel (standard drill)
   c. special super-high-speed steel (standard drill, Union Twist Drill Co.)

4. Cutting fluid

   a. dry
   b. emulsion 1:20
   c. sulfurized mineral oil
   d. plain mineral oil
   e. Stuart's "Thred Kut"

TEST EQUIPMENT

All the torque and thrust tests were run on a Barnes 201-1/4 box column, geared-head drill press (Fig. 1). The forces were measured with a dynamometer mounted directly on the drill-press table. The dynamometer used electrical-resistance strain gages to pick up the thrust forces and a linear variable differential transformer to pick up torque. Both the thrust and torque signals were recorded on a Sanborn Twin-Viso Recorder.

The materials cut in this series of tests were

Ti-75A, commercially pure titanium
Ti-150A, titanium alloy, 1.3% Fe, 2.7% Cr
RC-130B, titanium alloy, 4% Al, 4% Mn
RC-130A, titanium alloy, 1% Al, 7% Mn
SAE-1045 steel, 0.45% C, 0.6-0.9% Mn, 0.55% max S

All the preliminary and most drill-design testing was on Ti-75A.

The following is a listing of all drills used in the drilling experiments.

Variable diameter series:

1/4 inch	Standard	HSS	SS	blued	jobbers	drill
3/8 inch	Standard	HSS	SS	blued	jobbers	drill
1/2 inch	Standard	HSS	SS	blued	jobbers	drill
1 inch	Standard	HSS	TS	blued	jobbers	drill

Drill design series

3/8 inch	Standard	HSS	SS	blued	jobbers	drill
3/8 inch	High helix	HSS	SS	blued	jobbers	drill
3/8 inch	Low helix	HSS	SS	blued	jobbers	drill
3/8 inch	Straight flute	HSS	SS	blued	jobbers	drill
3/8 inch	Heavy duty	HSS	SS	blued	jobbers	drill
3/8 inch	Polished flutes	HSS	SS	blued	jobbers	drill
3/8 inch	Auto long	HSS	SS	blued	(extra long drills)	
3/8 inch	Auto short	HSS	SS	blued	(medium long drills)	
3/8 inch	Stub Screwmachine	HSS	SS	blued	(short drills)	
3/8 inch	Standard split point	HSS	SS	not blued	jobbers	drill
3/8 inch	Standard split point	HSS	SS	blued	jobbers	drill
3/8 inch	Carbon steel			not blued	jobbers	drill
3/8 inch	Heavy duty super	HSS	SS		jobbers	drill

TEST RESULTS

Figures 2 and 3 are summary curves showing the torque and thrust values for the various work materials using two drill sizes. It will be noted that RC-130B always requires the greatest amount of torque and thrust, regardless of feed or drill size. Of the remaining materials, there is no positive trend to indicate that any one grade of titanium is always the lowest in torque or thrust. All except RC-130B had approximately the same torque and thrust as SAE 1045 steel.

Figure 4 is a table giving torque, thrust and unit horsepower values for all materials when using a 1/2-inch HSS drill at a feed of 0.009 ipr. Again it will be noted that RC-130B produces the higest values throughout, while RC-130A requires the lowest torque and unit horsepower. The other materials are intermediate. Except for RC-130A, the trend in torque and thrust is the same. The thrust value for RC-130A was higher than expected in view of the torque and unit-horse-power values.

Figures 5 and 6 are summary curves of torque and thrust as affected by feed and drill diameter. Data points for these curves were obtained from the curves on Figs. 7 through 16. RC-130B had high torque and thrust when using heavy feeds or large-diameter drills, but the torque and thrust values were comparable to the other materials when using light feeds. The equations for torque and thrust, Fig. 4, had exponents, or slopes, typical of most steels. The torque increased as 0.85 power of the feed and 1.73 power of diameter except for RC-130B. These exponents indicate better efficiency when using heavier feeds and larger diameter drills.

The effect of cutting speed for Ti-75A, Ti-150A, and RC-130B on torque and thrust is shown in Figs. 17, 18, and 19. The torque was not affected by a change in cutting speed. In some cases the dispersion of data was quite pronounced, but in view of the overall results it was felt that straight-line trends as shown would be most indicative. The decrease in thrust with increasing speeds for Ti-75A at 0.004 feed was caused by the higher temperature generated, which made the thin chips flow easier.

The effect of drill design on torque and thrust is shown in Figs. 20 through 23. Figures 20 and 21 show the difference between torque and thrust when drilling shallow holes (less than one drill-diameter deep) and deep holes (more than three drill-diameters deep) on Ti-75A. The high-helix drills give superior performance regardless of feed or depth of hole. The straight-flute and low-helix-angle drills were the poorest, particularly when drilling deep holes.

When drilling Ti-150A and RC-130B the same trend of results were obtained as shown in Figs. 22 and 23. This means that regardless of titanium alloy, a high-helix-angle drill will require less torque and thrust than the other designs tested. These results are consistent with the findings regarding single-point cutting tools, where it was shown that high rake angles reduce forces and prolong tool life if coupled with adequate rigidity.

The effect of cutting fluids on torque and thrust is shown in Fig. 24 and 25. Regardless of the cutting fluid used, less torque was required than when drilling dry. The lowest torque values were obtained when using Stuart's "Thred Kut", which is a highly chlorinated and sulfurized mineral oil. The cutting fluid with the least effect was a 1:20 emulsion of soluble oil in water.

The thrust curves, Fig. 25, indicate that for the lower feeds, dry cutting produces less thrust than cutting with fluids. At the higher feeds Stuart's "Thred Kut" is again superior to all other fluids. This cutting fluid gave the best overall performance.

DRILL LIFE

The data presented on drill life, although closely correlated to the preceding section of the report, were obtained under different test conditions. The purpose was to determine the life of the drill, torque and thrust not being considered. To obtain greater rigidity and less vibration, a Kearny and Trecker Model K vertical-spindle milling machine was used in place of the Barnes drill press. The work was clamped in a vise mounted on the table. Feeds were obtained by power-feeding the head downward. All holes were drilled one inch deep, and the total number of holes drilled before failure occurred constituted drill life. Flank wear of 0.030-inch was considered failure. The wear was measured with a Gaertner toolmaker's microscope.

The tool-life results obtained for different drill lengths and helix angles are shown in Figs. 26 and 27 with regard to helix angle. The standard drill with the KK treatment outperformed all other types tested. The standard drill without the KK treatment was still superior to all other types. The poorest results were obtained with the low-helix-angle drill.

With regard to drill length, the standard drill length again was superior to all other types tested, and the KK treatment improved the performance. The type of drill failure when drilling the one-inch-deep holes was due to accordian pleating of hot, thin chips which blocked the flow of cutting fluid, thereby increasing the temperature, torque, and thrust. The expected increase in tool life with the short, rigid stub drills, did not materialize because the more restricted flute space caused more chip jamming. Later tests with shortened standard drills showed increased rigidity to be a benefit.

Figures 28, 29, and 30 show typical chip formation when drilling the three grades of titanium. Chip specimens are shown for the various feeds used on the tests. It may be seen that a less tightly spiraled chip occurs for all materials at the lower feeds. The spiral of the chip becomes tighter as the feed increases. In deeper holes the chips fold or accordian pleat, blocking the cutting fluid and jamming the chips. The hot, thin chips which result when drilling titanium fold more easily than when cutting steel.

Drill dulling changes chip formation from hole to hole as shown in Fig. 31. Sharp drills form a tightly wound, continuous spiral chip which changes to a tightly folded or accordian pleated chip as the drill dulls. The higher temperatures of the chip, with dull drills, cause a softening and folding of the thin chips, thus clogging the flutes and causing drill failure.

Super-high-speed-steel drills of the heavy duty type with a crankshaft point were purchased from the Union Twist Drill Company to determine if the additional heat resisting properties of the super-high-speed steel would be of benefit. When run at the same speed as the Moly type of high-speed drills, 135 holes were drilled without reaching 0.010 flank wear. Moly HSS drills under the same conditions had a life of approximately 57 holes. When tested at a higher speed of 104 fpm, the tool life was drastically reduced to 22 holes. It may be concluded that super-high-speed steel gives longer life.

A carbide-tipped 3/8-inch-diameter heavy-duty low-spiral drill was tested on Ti-75A. Excessive chip clogging, pickup on the margin of the carbide tip, and extreme overloading caused heavy wear and chipping. Carbide-tipped drills are therefore not recommended for titanium. Carbon tool-steel drills were tested at 14 fpm but failed in the first hole indicating that their heat resisting properties are not satisfactory.

The use of mercury as a cutting fluid was tried by submerging the work under mercury during drilling. The effect on chip formation was remarkable, since all chips were finely broken, even when cutting at higher speeds. The high heat conductivity of mercury caused quenching and brittling of the chips. In the interest of safety, it should be noted that mercury vapors are extremely poisonous.

CONCLUSIONS

1. A high-helix angle drill produces lower torque and gives best chip clearance.
2. The short-length stub drill which should have given greater tool life due to increased rigidity, proved to have excessive chip interference due to a heavy web and a short flute length.
3. In general, titanium produces higher thrust values than steel, indicating the need for more rigidity when drilling titanium, particularly RC-130B.
4. Shortening standard drills increases the rigidity and lengthens tool life.
5. Carbon tool steel and carbide-tipped drills are not recommended.
6. The recommended cutting speed for commercially pure titanium is around 70 fpm and for the alloys around 30 fpm.
7. It is necessary to provide adequate cooling to prevent overheating of the drills and plasticity of the chips. Emulsions are recommended for higher cutting speeds.

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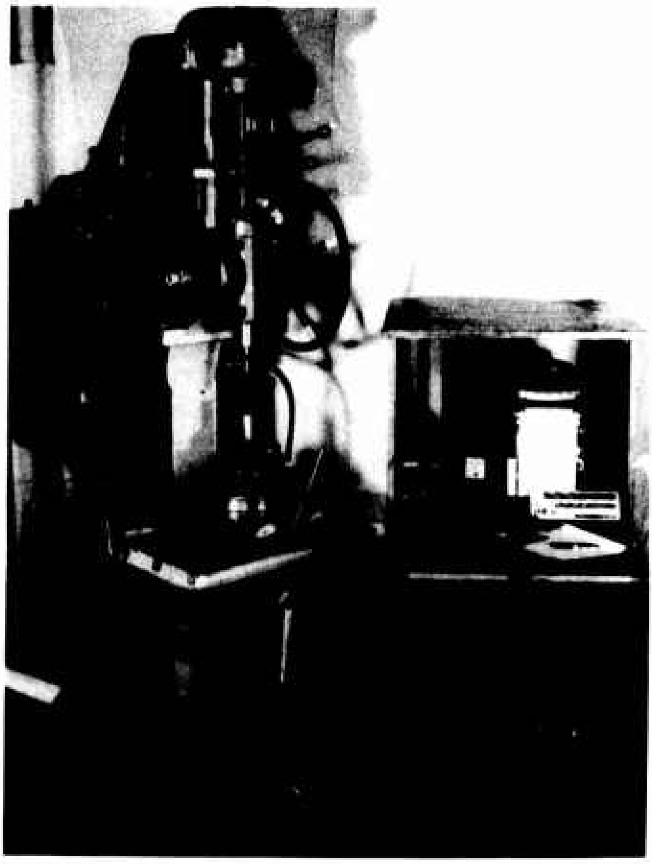


BARNES 201 1/4 GEARED HEAD DRILL PRESS

WITH DYNAMOMETER AND WATTMETER

(THE SANBORN EQUIPMENT IS NOT SHOWN)

FIG. 1

DRILLING TESTS

MATERIALS vs TORQUE & vs THRUST

I INCH DIA. STANDARD H.S.S. DRILLS

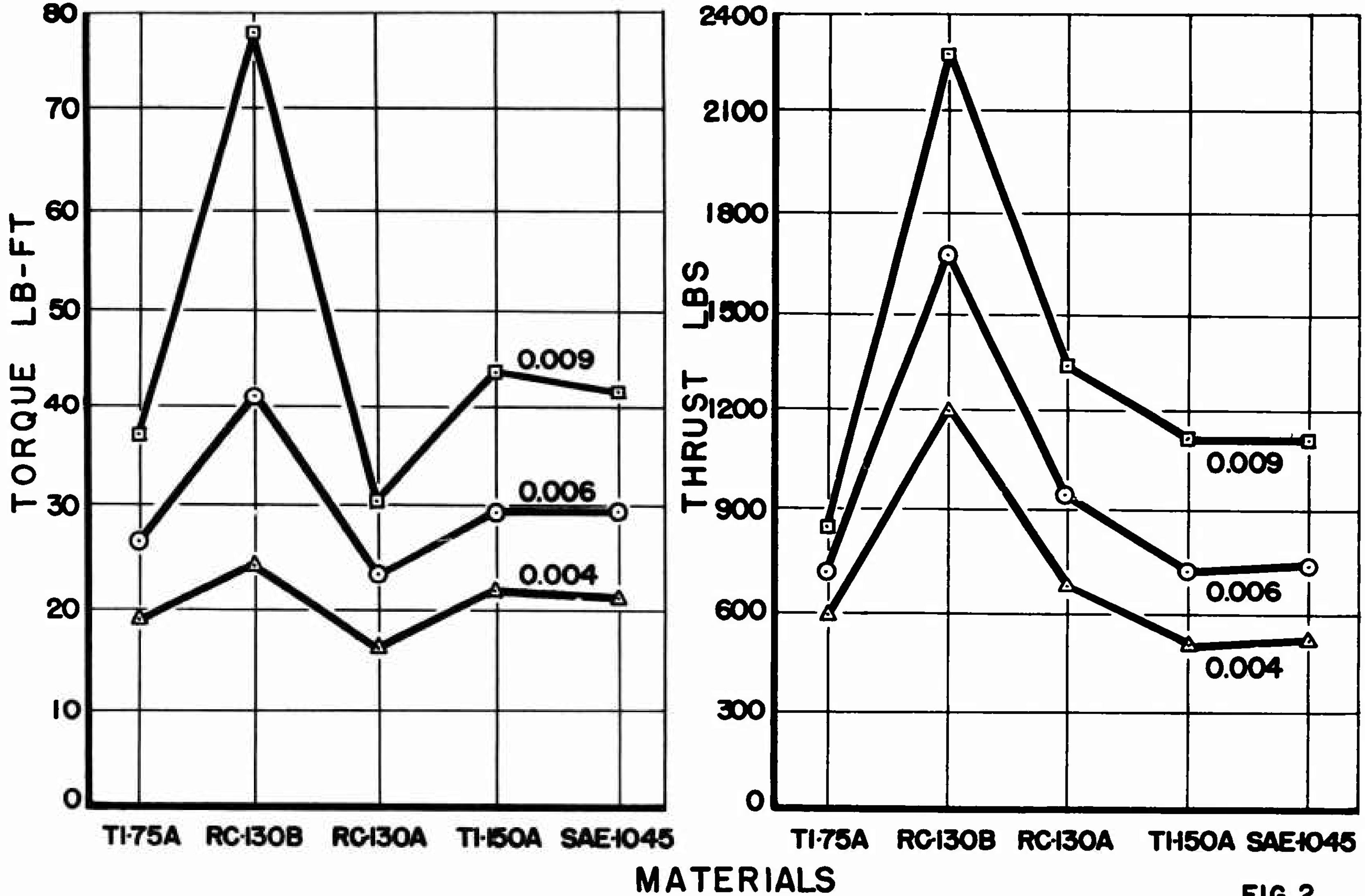


FIG. 2.

DRILLING TESTS

MATERIALS vs TORQUE & vs THRUST

1/2 INCH DIA. STANDARD H.S.S. DRILLS

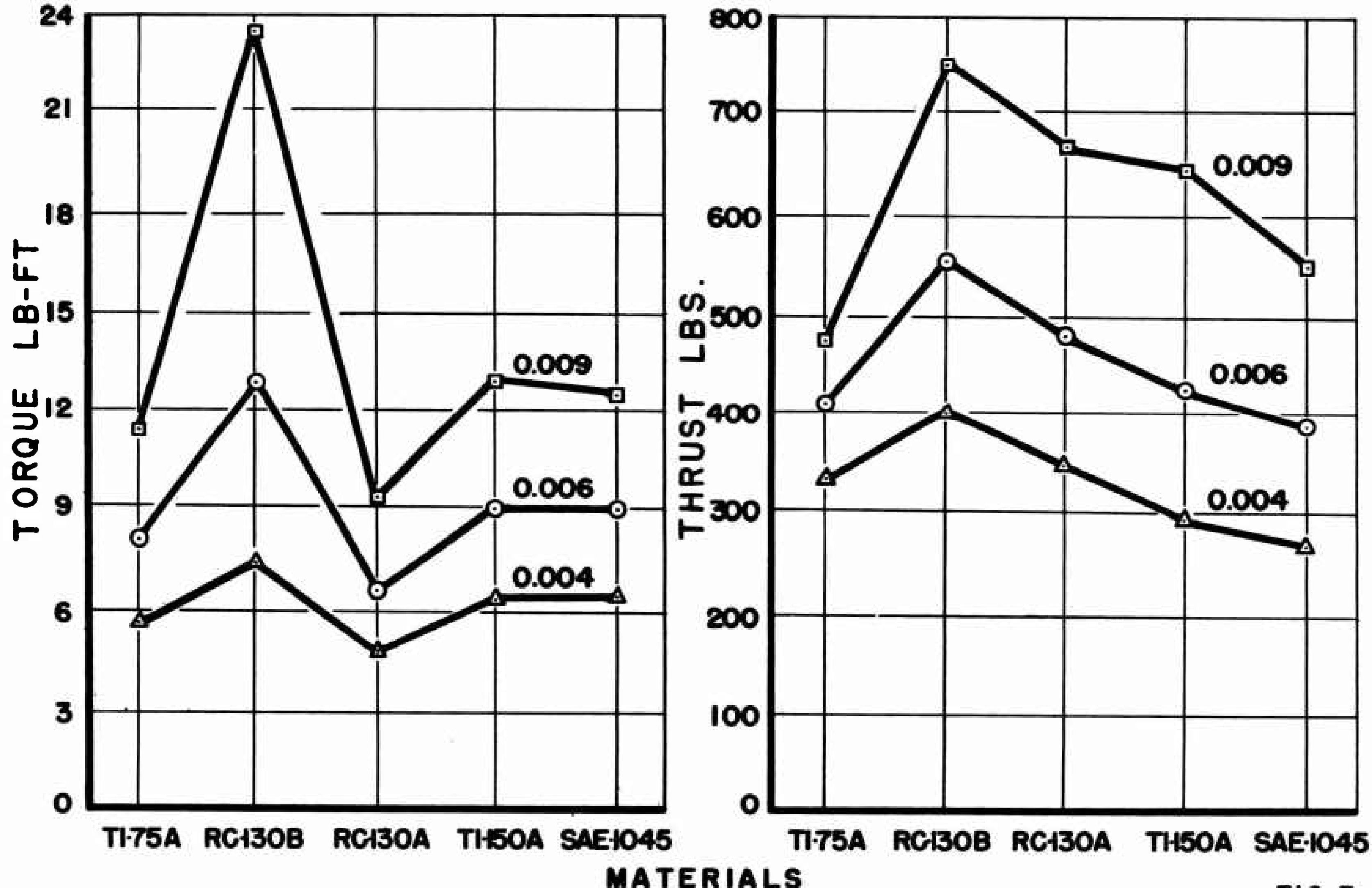


FIG. 3.

DRILLING TORQUE & THRUST FORMULAS WITH CONSTANTS AND EXPONENTS FOR TITANIUM ALLOYS

MATERIAL	TORQUE			THRUST			1/2" HSS DRILL, 225 RPM, .009 IPR		
	a	b	C	z	y	K	TORQUE	THRUST	HP/in³/min
TI-75 A	0.84	1.73	1900	0.42	0.84	6300	10.9	480	1.18
TI-150 A	0.87	1.73	2550	0.96	0.78	101000	13.2	642	1.42
RC-130B	1.43	1.73	65000	0.81	1.60	105000	23.4	732	2.52
RC-130A	0.84	1.73	1680	0.82	1.00	63800	9.2	665	0.99
SAE 1045	0.85	1.73	2310	0.90	1.00	75500	13.0	532	1.40

TORQUE $= T = c \times f^{a} \times d^{b}$

THRUST $= B = k \times f^{z} \times d^{y}$

FIG. 4.

DRILLING TITANIUM

COMPOSITE CURVES FOR TORQUE AND THRUST VALUES WHEN DRILLING TI·75A, TI·150A, RC·130A, RC·130B & SAE·1045. DRILL: 1/2" HSS, SPEED: 29.4 FPM

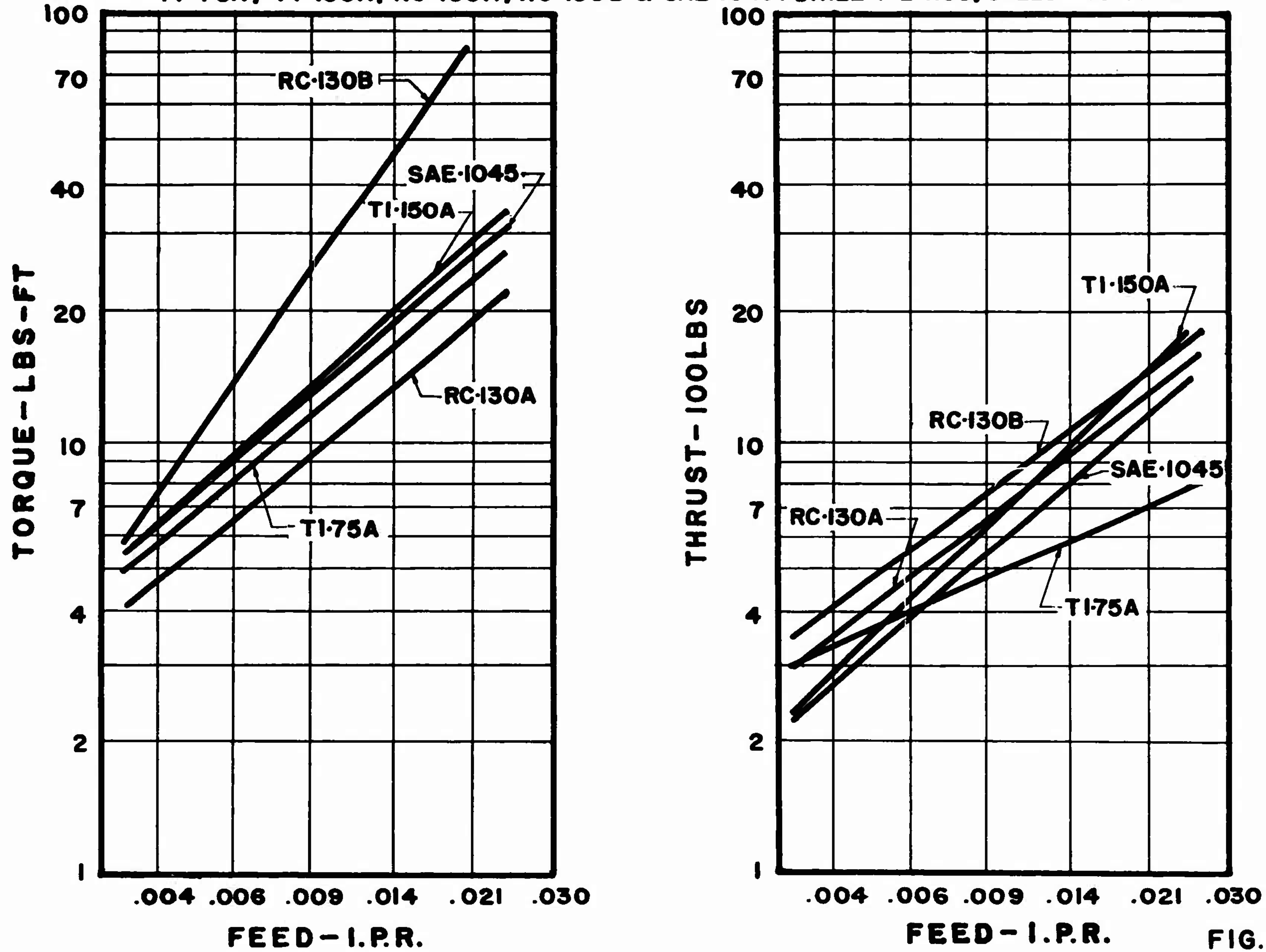


FIG. 5.

DRILLING TITANIUM

COMPOSITE CURVES FOR TORQUE AND THRUST VALUES WHEN DRILLING TI-75A, TI-150A, RC-130A, RC-130B, & SAE 1045. SPEED: 29.4 FPM, FEED: 0.009 IPR.

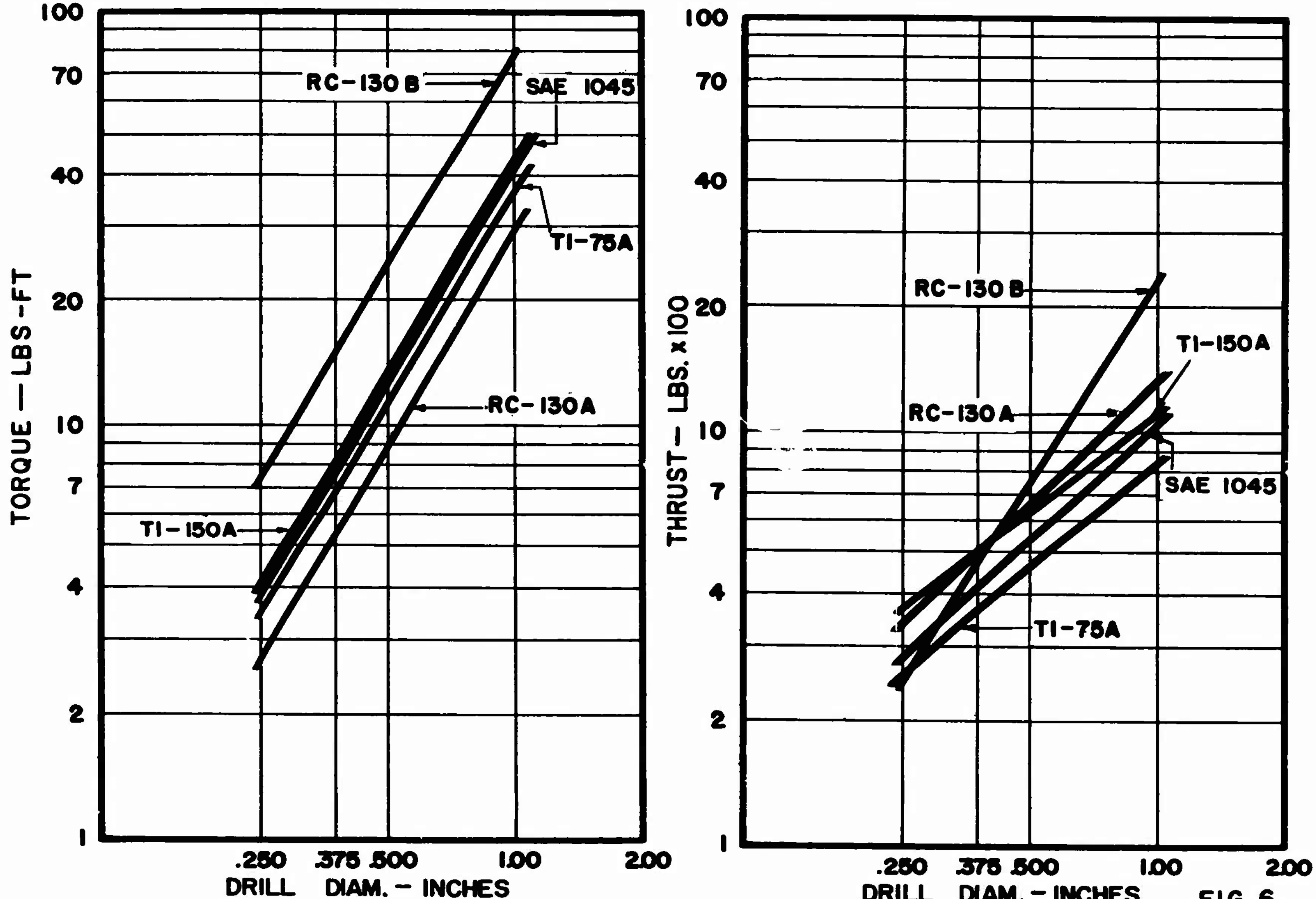


FIG. 6.

DRILLING TITANIUM

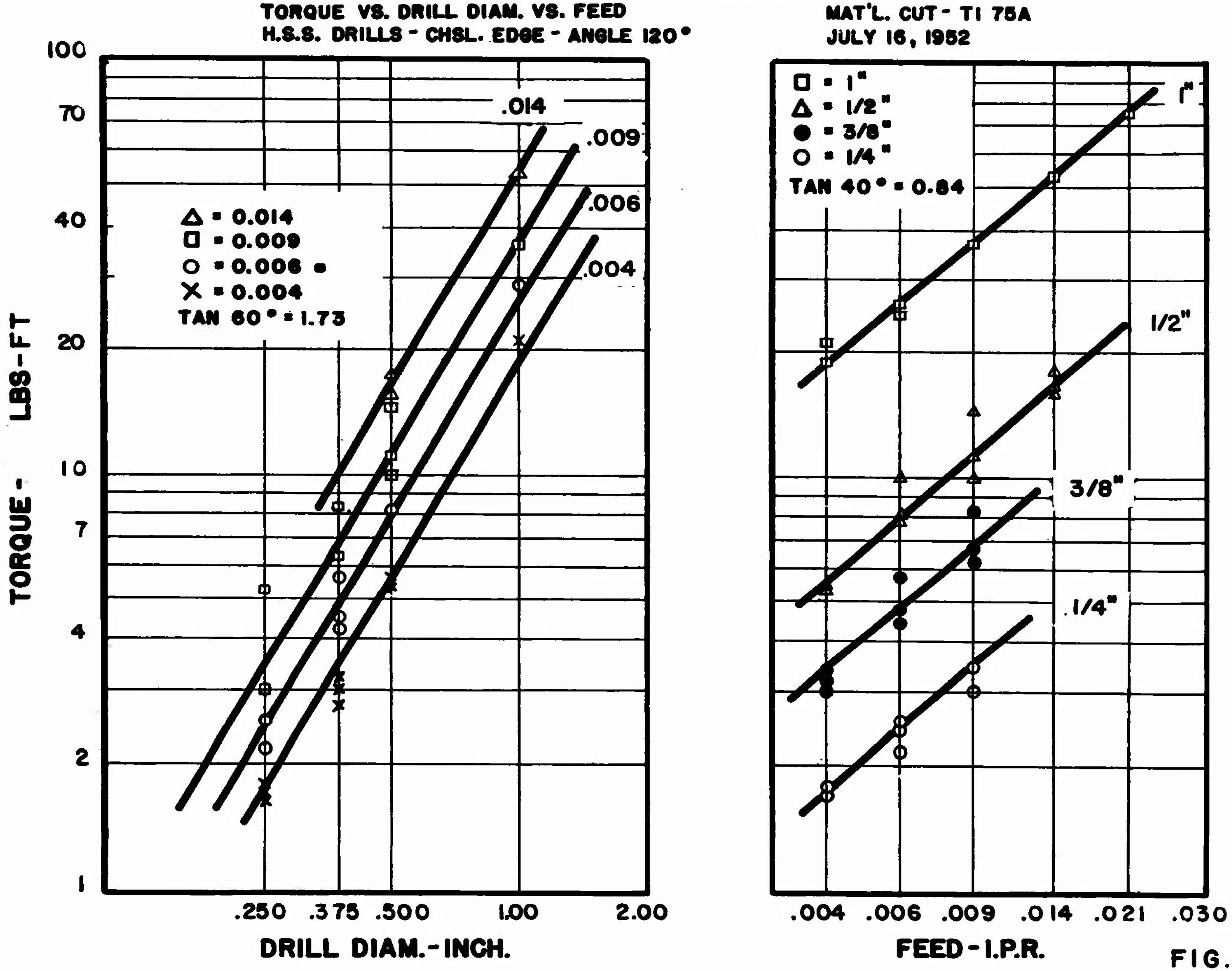


FIG. 7.

DRILLING TITANIUM

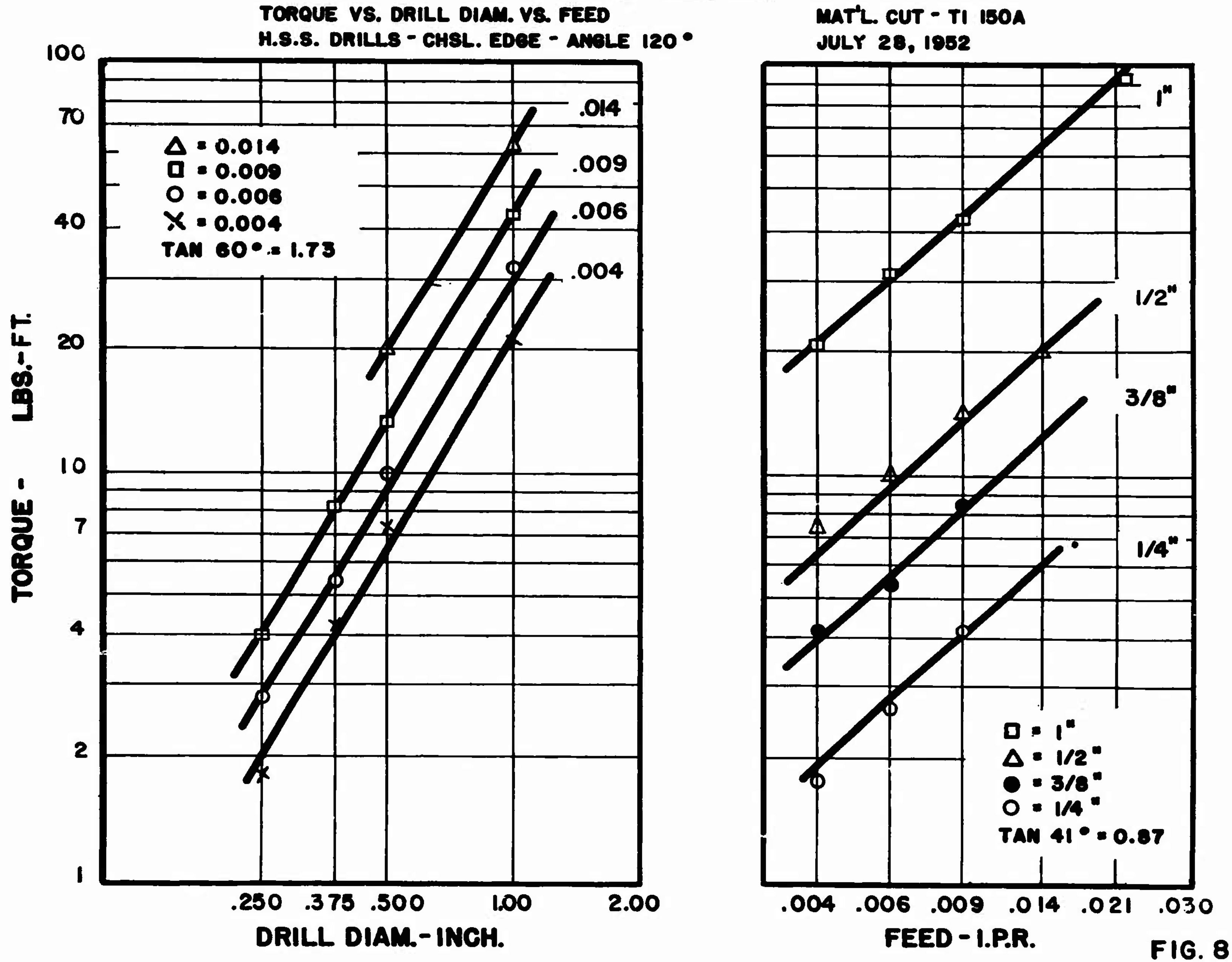


FIG. 8.

DRILLING TITANIUM

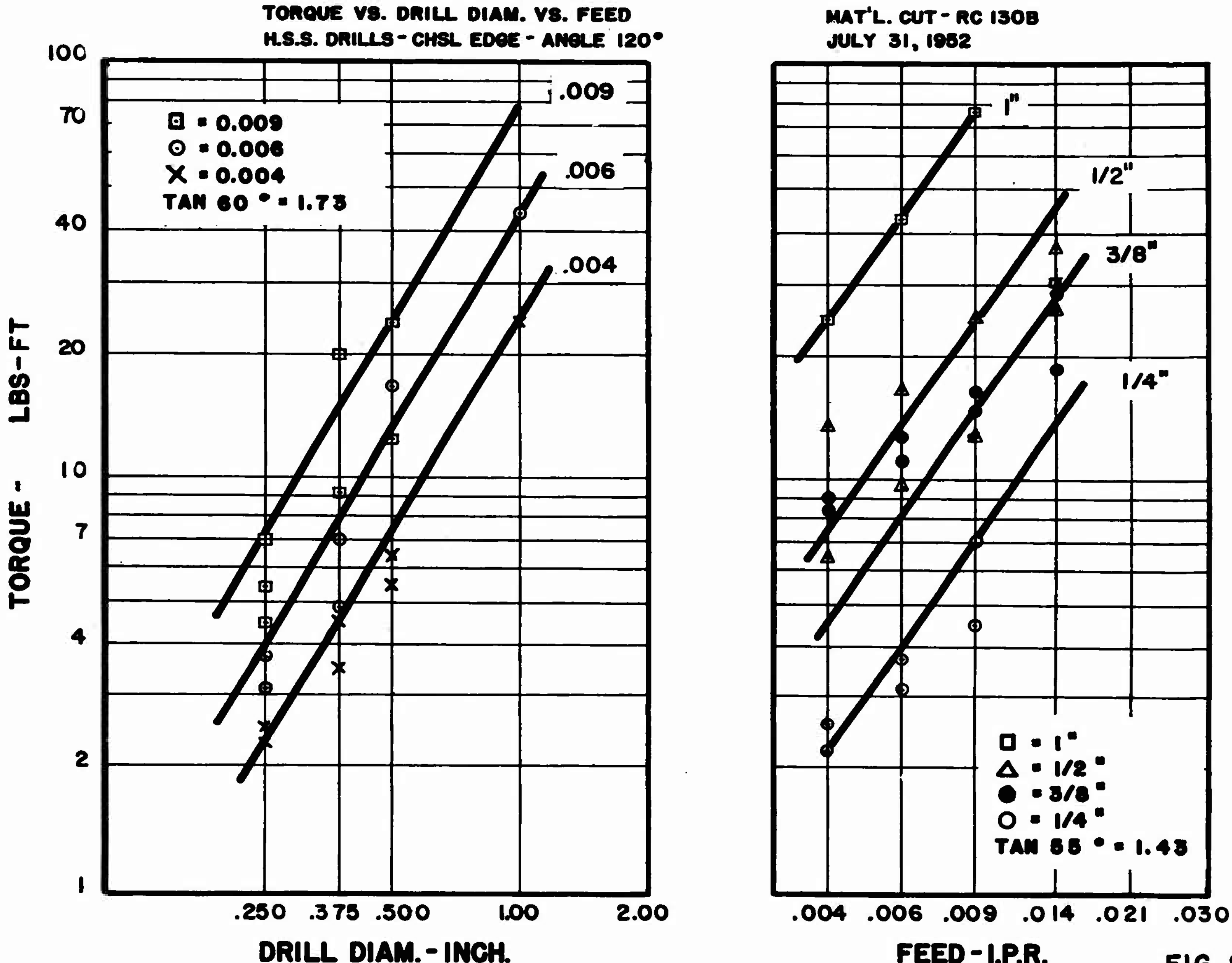


FIG. 9.

DRILLING TITANIUM

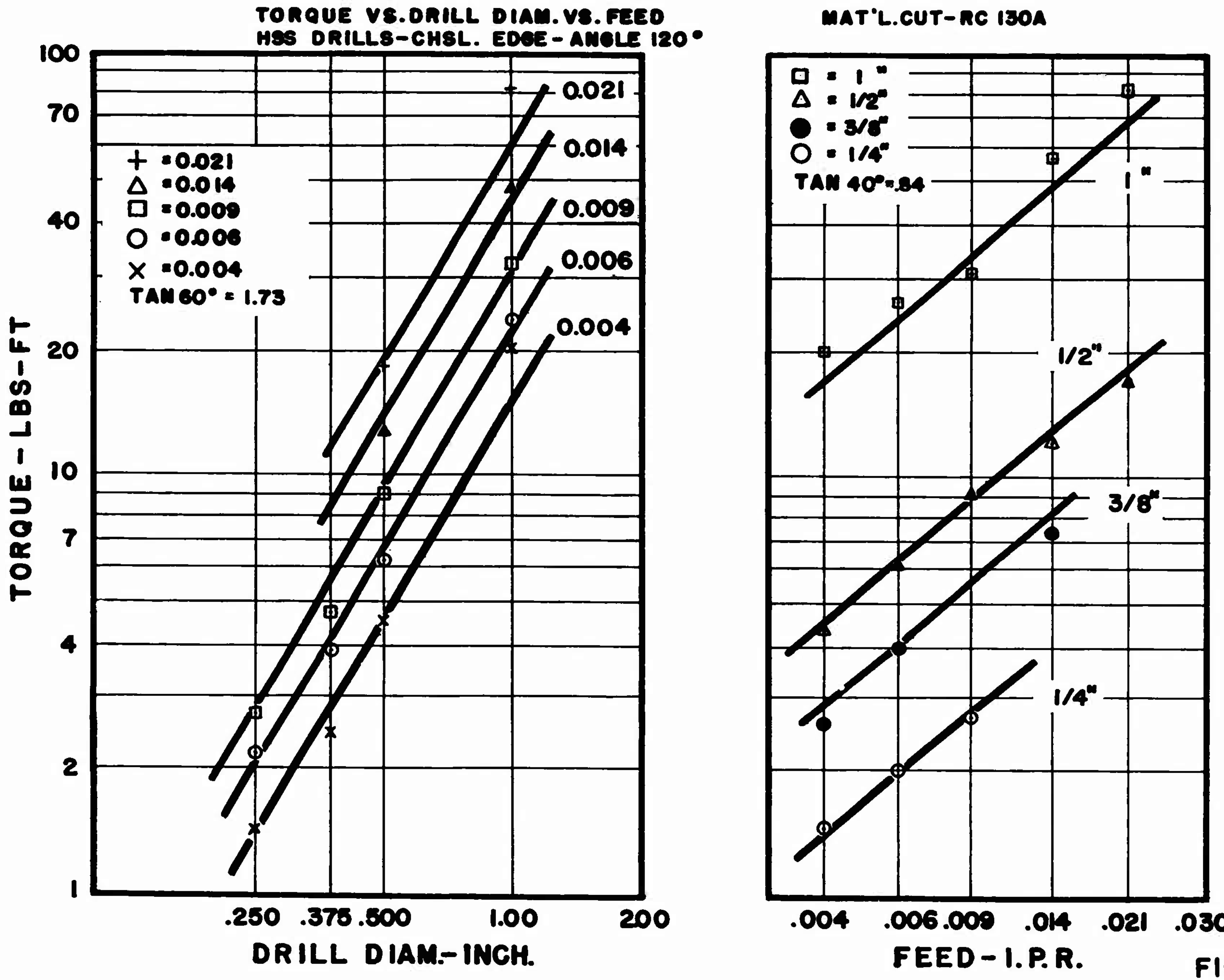


FIG. 10.

DRILLING TEST

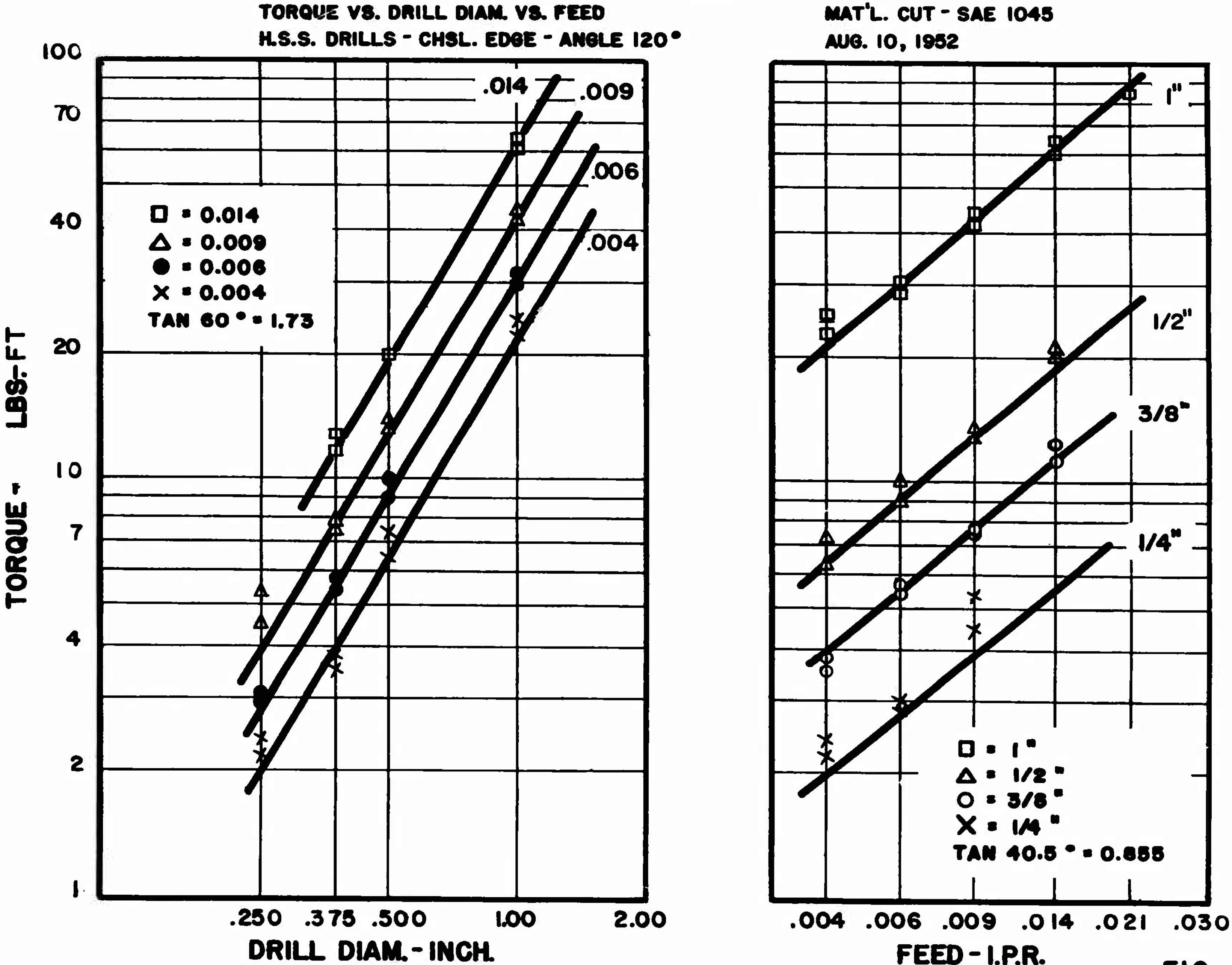


FIG. 11.

DRILLING TITANIUM

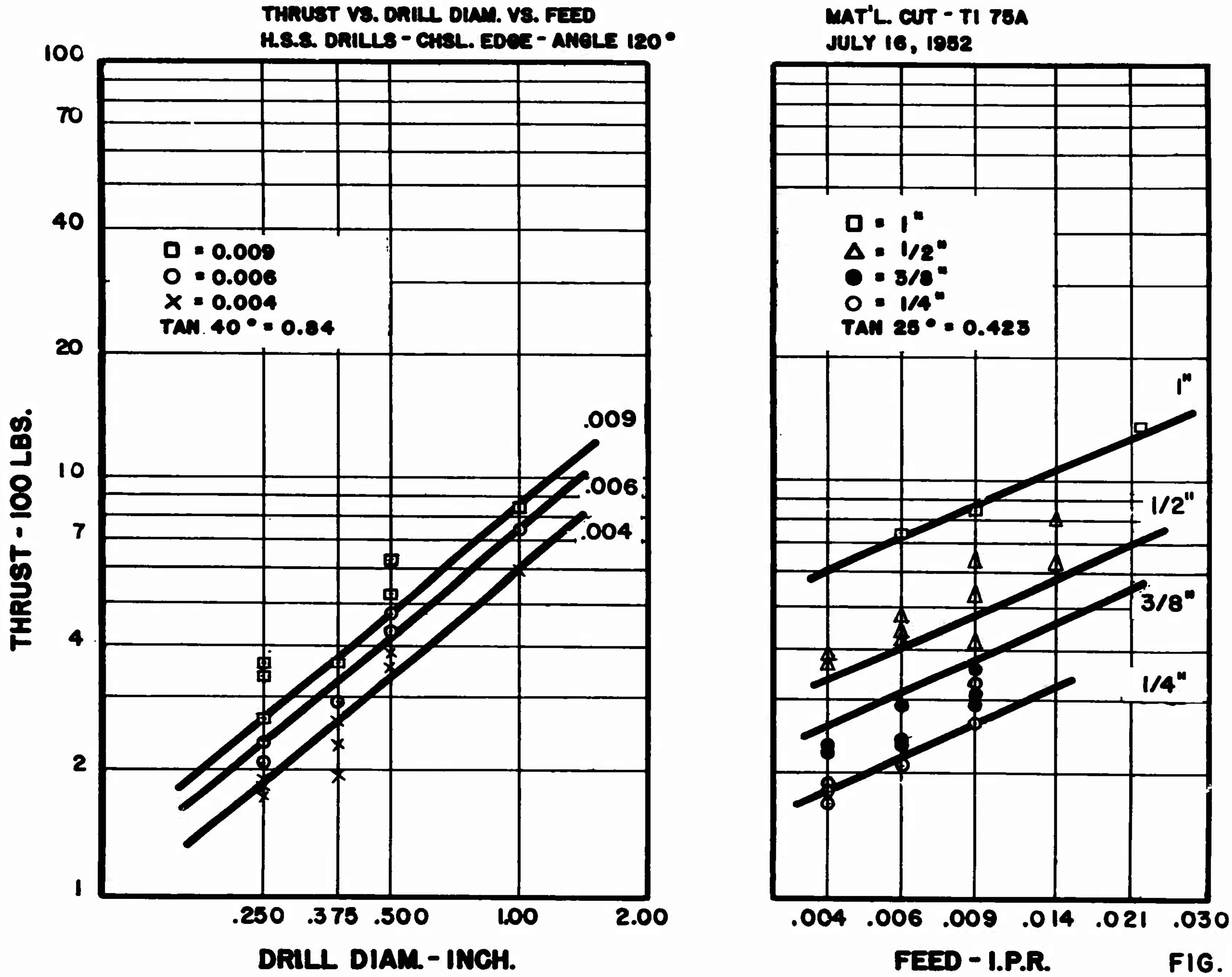


FIG. 12.

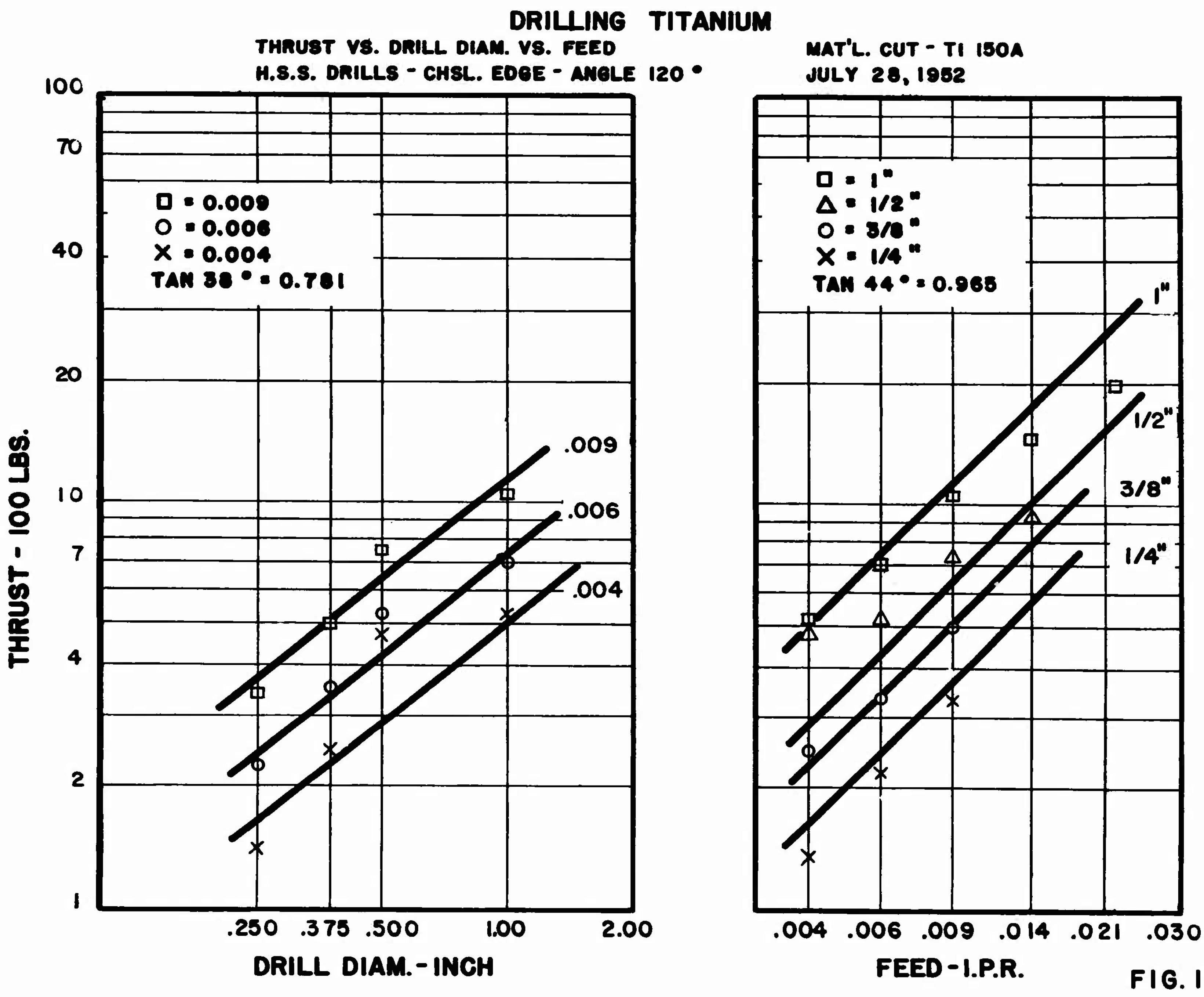

DRILLING TITANIUM
THRUST VS. DRILL DIAM. VS. FEED
H.S.S. DRILLS - CHSL. EDGE - ANGLE 120°
MAT'L. CUT - TI 150A
JULY 28, 1952
□ = 0.009
○ = 0.006
X = 0.004
TAN 38° = 0.781
□ = 1"
△ = 1/2"
○ = 3/8"
X = 1/4"
TAN 44° = 0.965
.009
.006
.004
1"
1/2"
3/8"
1/4"
100
70
40
20
10
7
4
2
1
THRUST - 100 LBS.
.250
.375
.500
1.00
2.00
DRILL DIAM.-INCH
.004
.006
.009
.014
.021
.030
FEED-I.P.R.

FIG. 13.

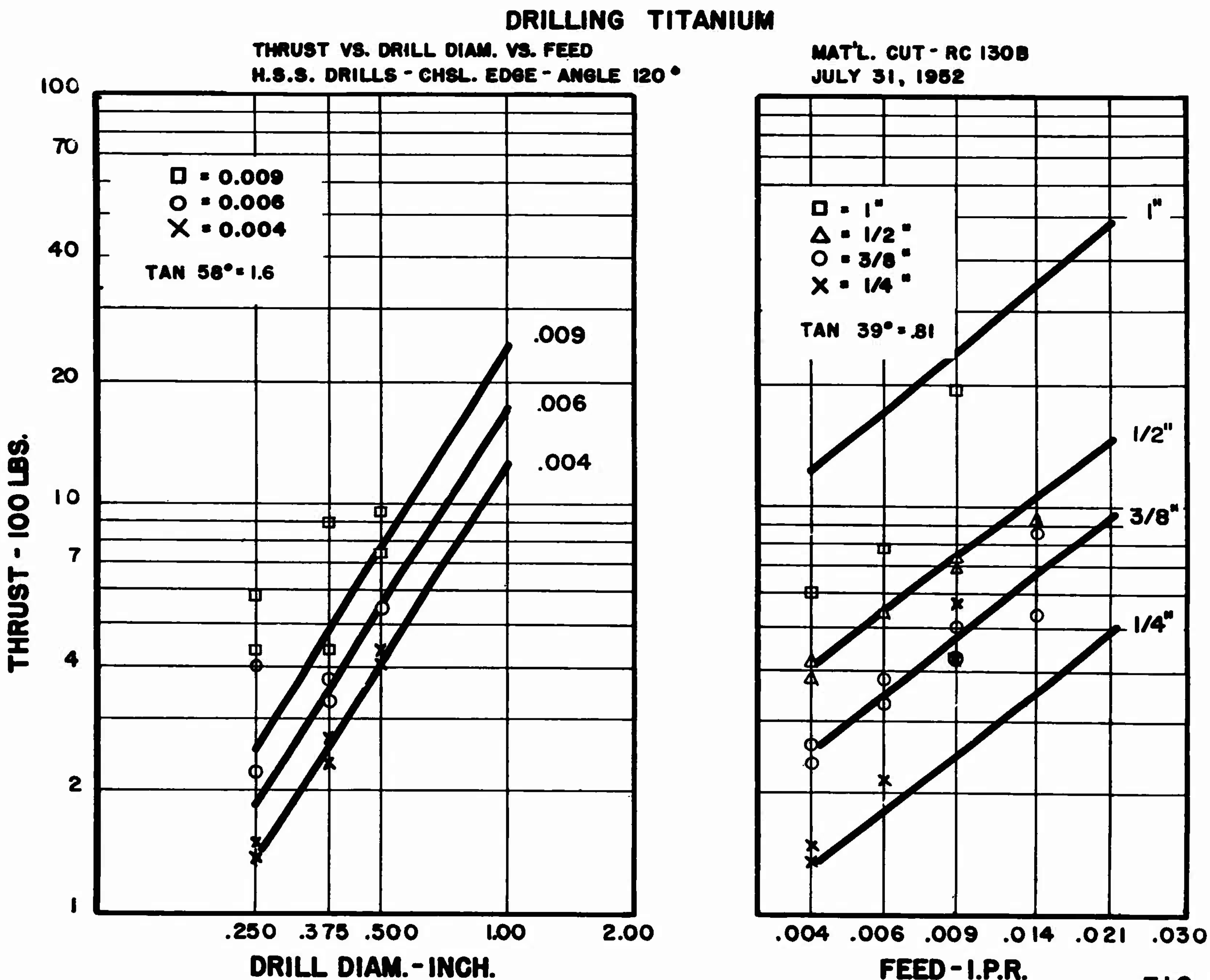

DRILLING TITANIUM
THRUST VS. DRILL DIAM. VS. FEED
H.S.S. DRILLS - CHSL. EDGE - ANGLE 120°
MAT'L. CUT - RC 130B
JULY 31, 1952
□ = 0.009
○ = 0.006
X = 0.004
TAN 58° = 1.6
.009
.006
.004
THRUST - 100 LBS.
100
70
40
20
10
7
4
2
1
.250
.375
.500
1.00
2.00
DRILL DIAM. - INCH.
□ = 1"
△ = 1/2"
○ = 3/8"
X = 1/4"
TAN 39° = .81
1"
1/2"
3/8"
1/4"
.004
.006
.009
.014
.021
.030
FEED - I.P.R.

FIG. 14.

DRILLING TITANIUM

THRUST VS. DRILL DIAM. VS. FEED
H.S.S. DRILLS-CHSL. EDGE-ANGLE 120°

MAT'L – RC 130A

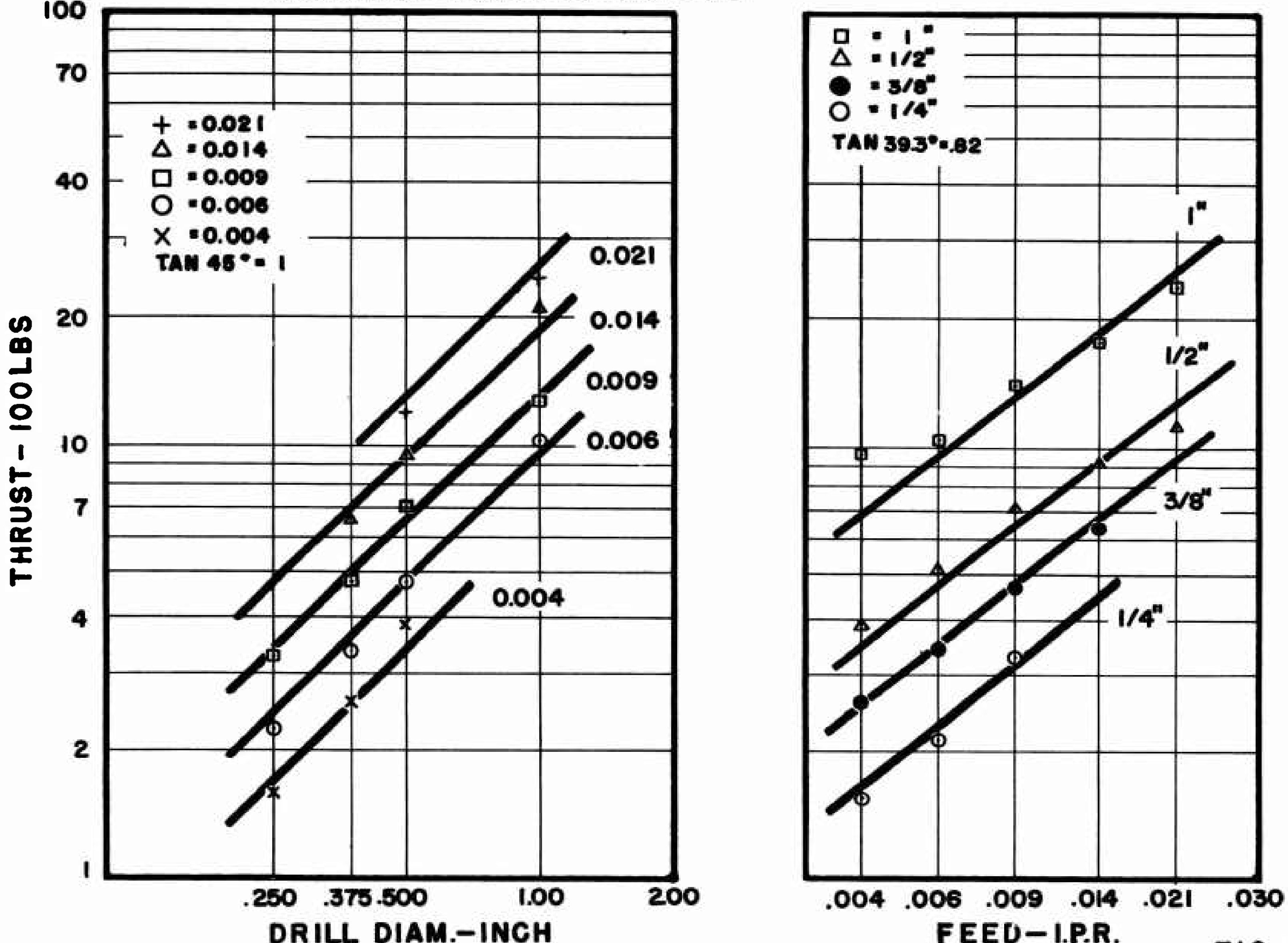


FIG. 15.

DRILLING TEST

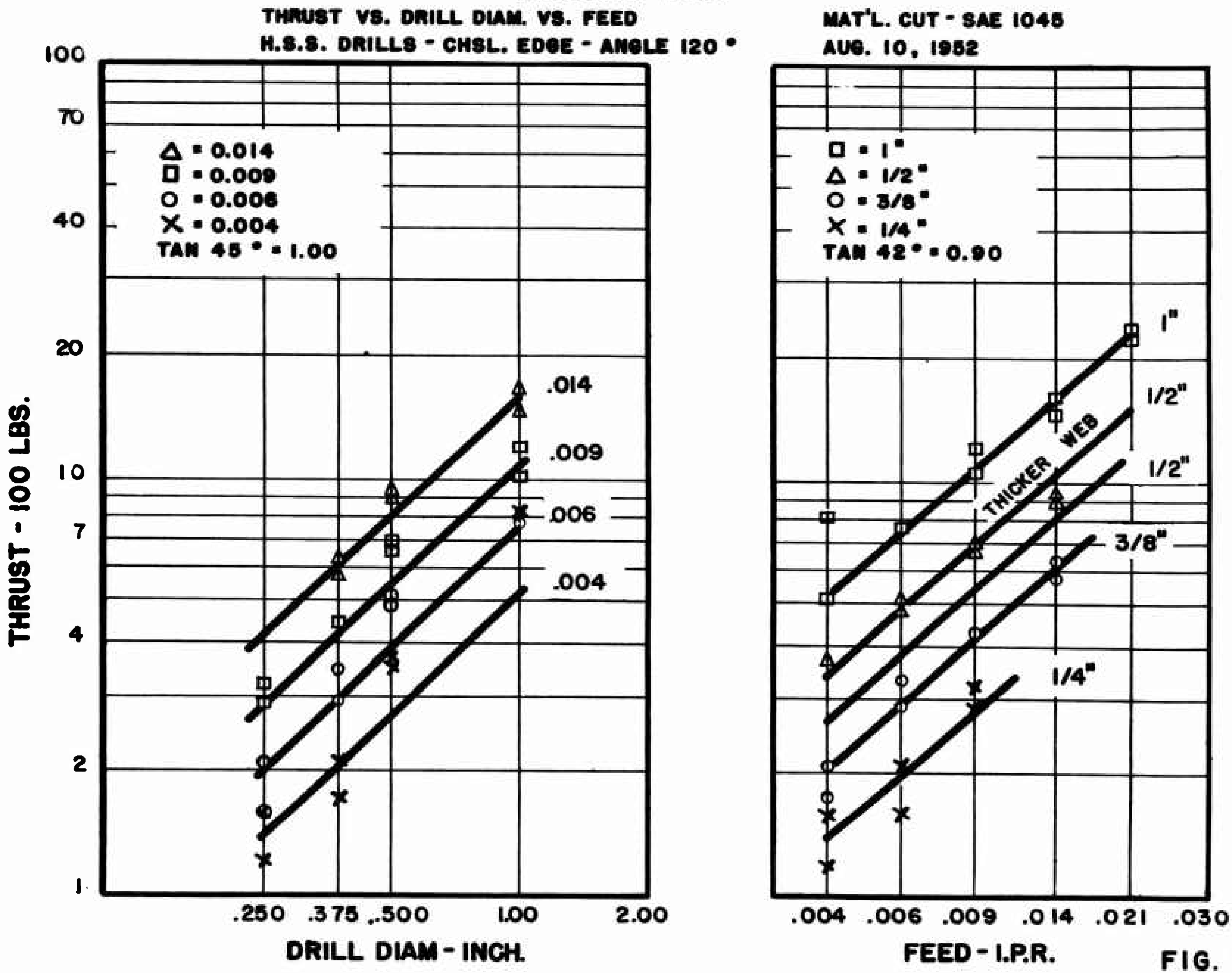


FIG. 16.

DRILLING TITANIAM

TORQUE & THRUST VS. SPEED MAT'L. CUT-TI·75A
H.S.S. DRILLS-CHSL.-ANGLE 120°-DIA. 3/8 INCH

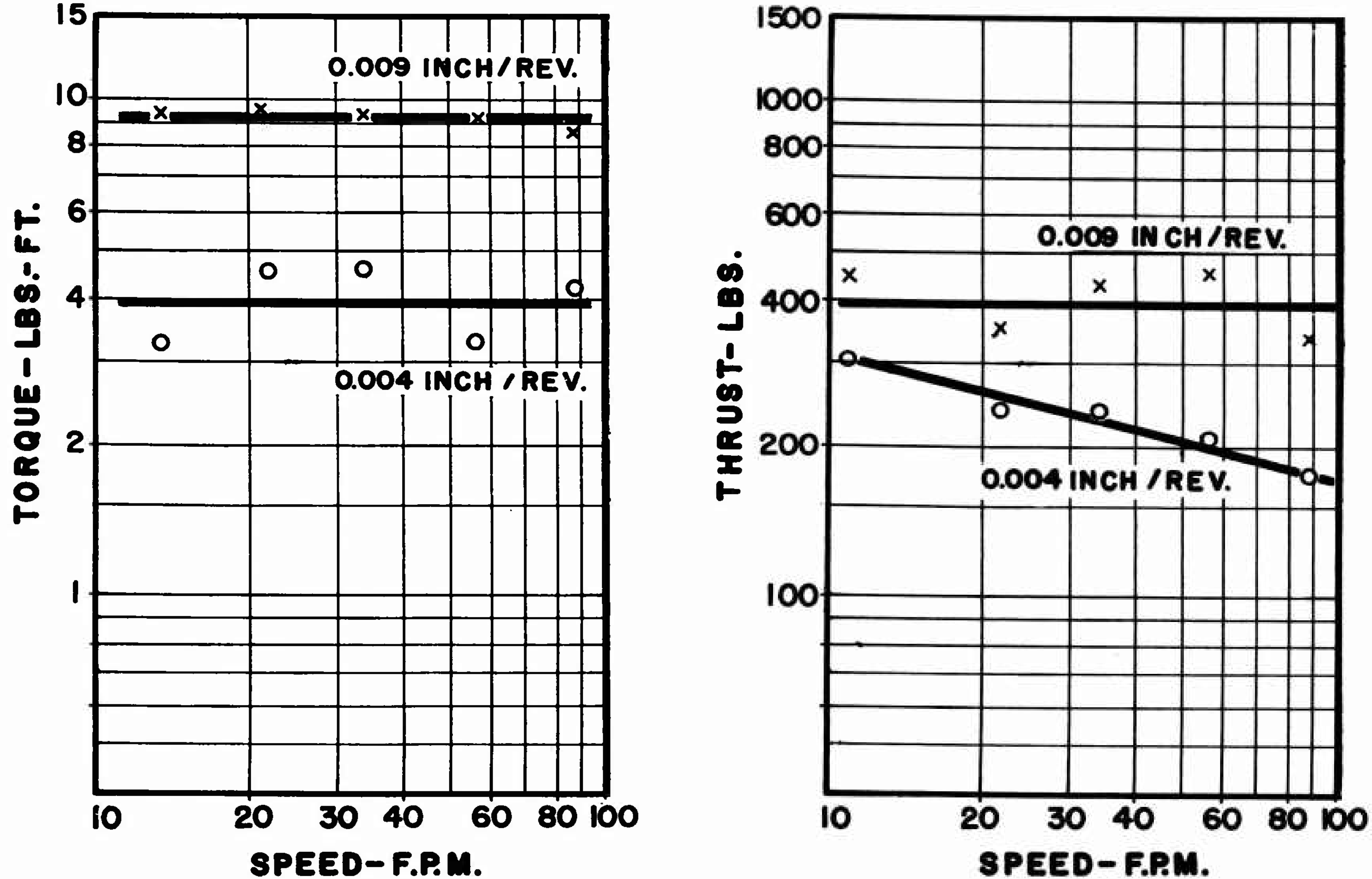


FIG. 17.

DRILLING TITANIAM

TORQUE & THRUST VS. SPEED MAT'L. CUT—TI·150A

H.S.S. DRILLS—CHSL.—ANGLE 120°— DIA. 3/8 INCH

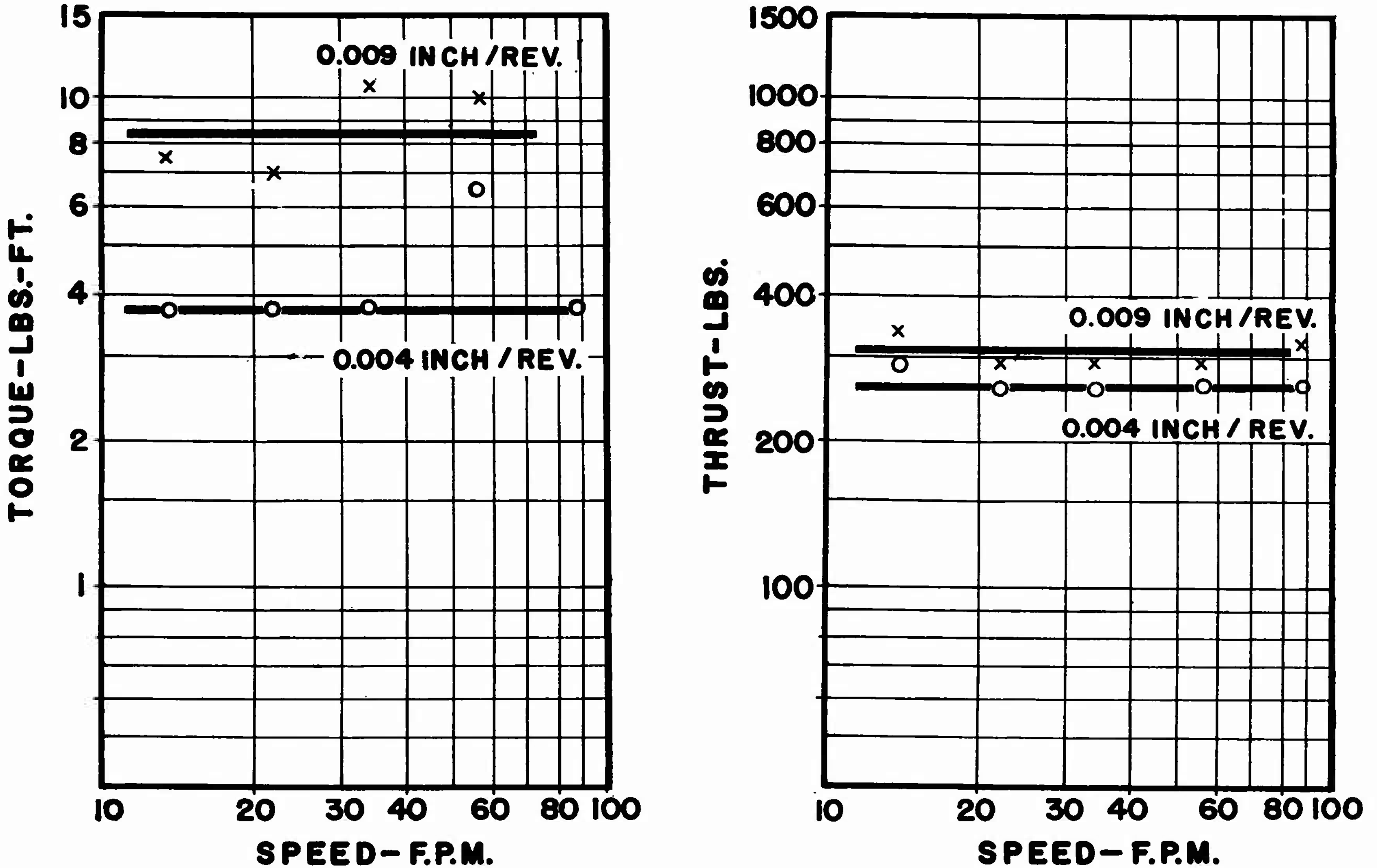
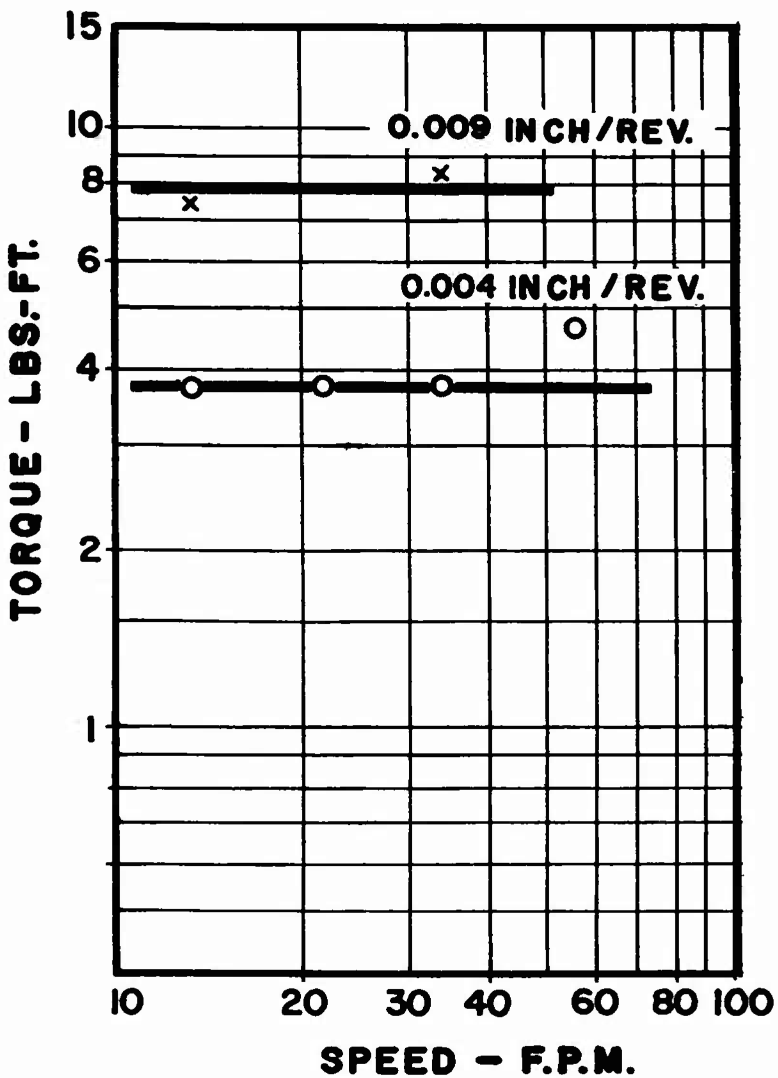


FIG. 18.

DRILLING TITANIAM

TORQUE & THRUST VS. SPEED MAT'L. CUT – RC 130B

H.S.S. DRILLS – CHSL. – ANGLE 120° – DIA. 3/8 INCH



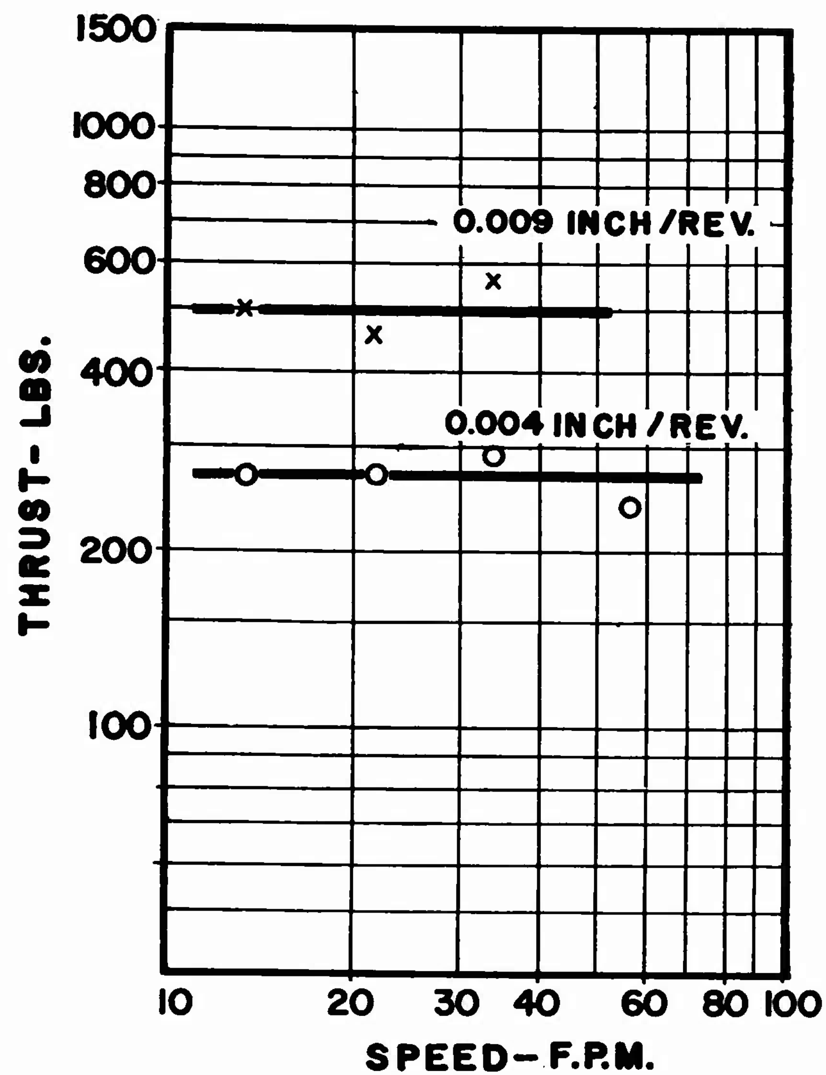


FIG. 19.

TORQUE & THRUST (FOR SHALLOW HOLES) vs. DRILL DESIGN

3/8" HSS DRILLS (AS RECEIVED) SPEED—225 RPM OR 22.1 FPM MATERIAL—TI-75A

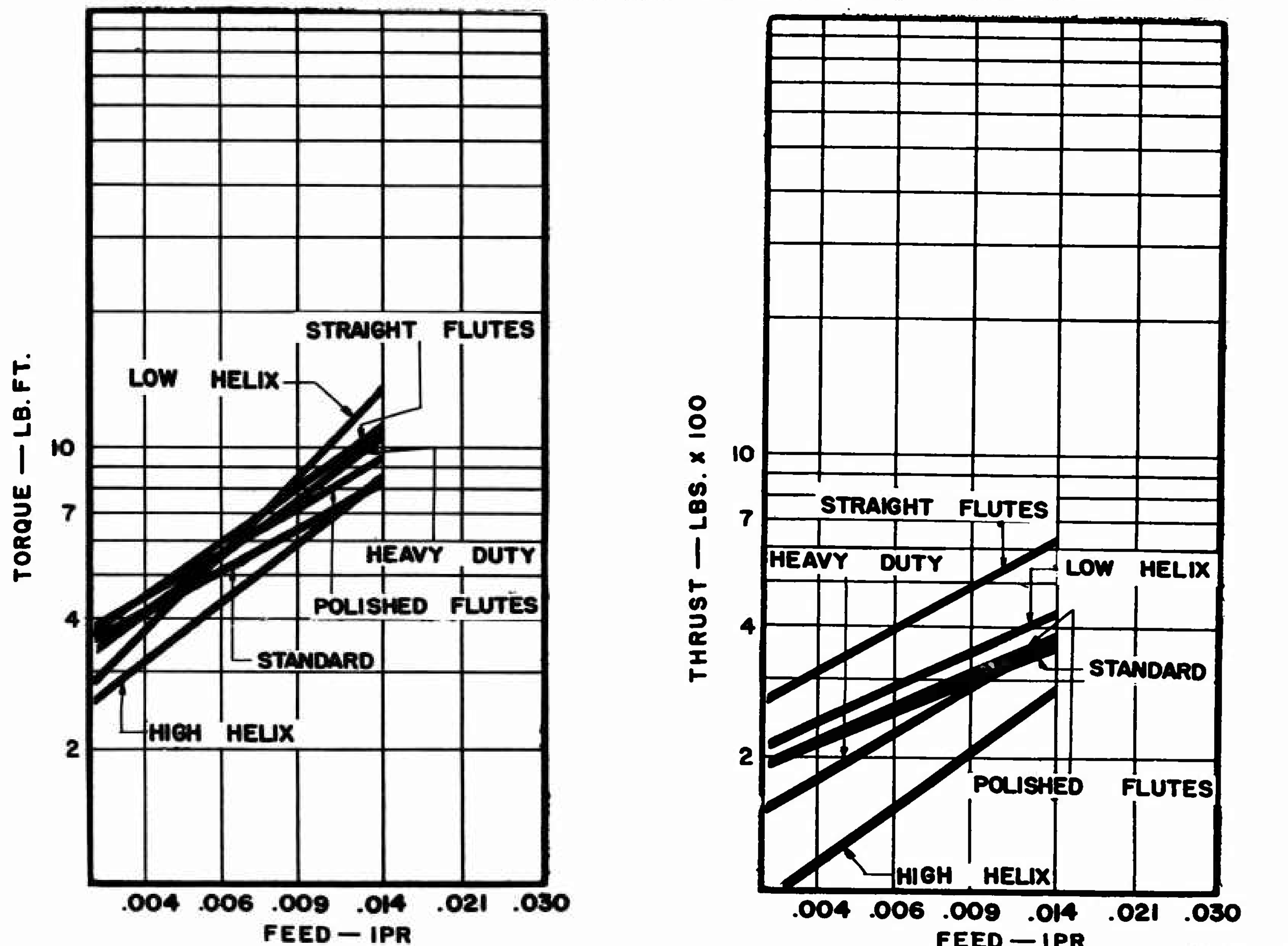


FIG. 20.

TORQUE & THRUST (FOR DEEP HOLES) VS. DRILL DESIGN

3/8" HSS DRILLS (AS RECEIVED) SPEED—225 RPM OR 22.1 FPM MATERIAL — TI-75A

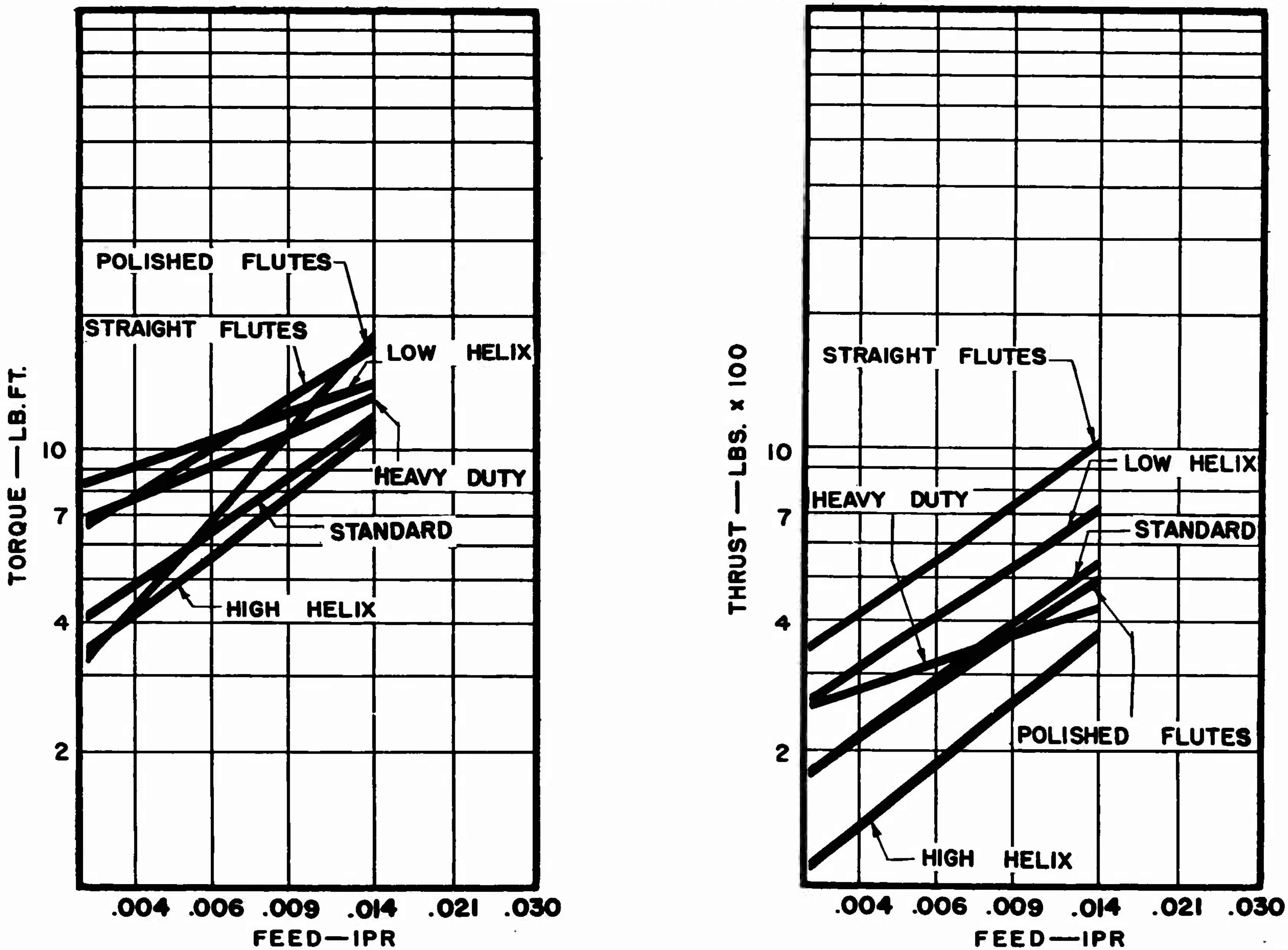


FIG. 21.

TORQUE & THRUST VS. DRILL DESIGN

3/8" HSS DRILLS (AS RECEIVED) SPEED — 225 RPM OR 22.1 FPM MATERIAL — TI-150A

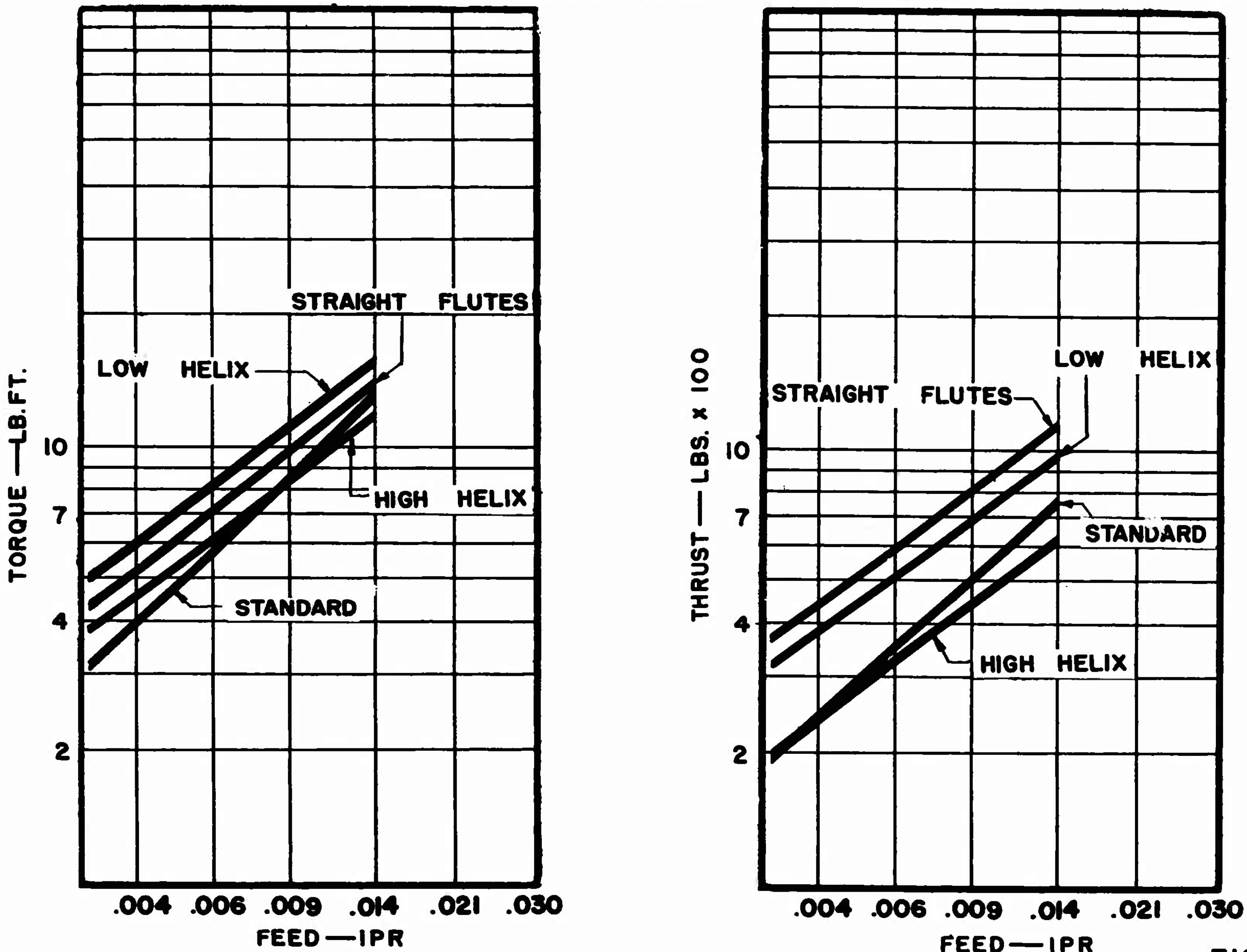


FIG. 22.

TORQUE & THRUST VS. DRILL DESIGN

3/8" HSS DRILLS (AS RECEIVED) SPEED — 225 RPM OR 22.1 FPM MATERIAL — RC-130B

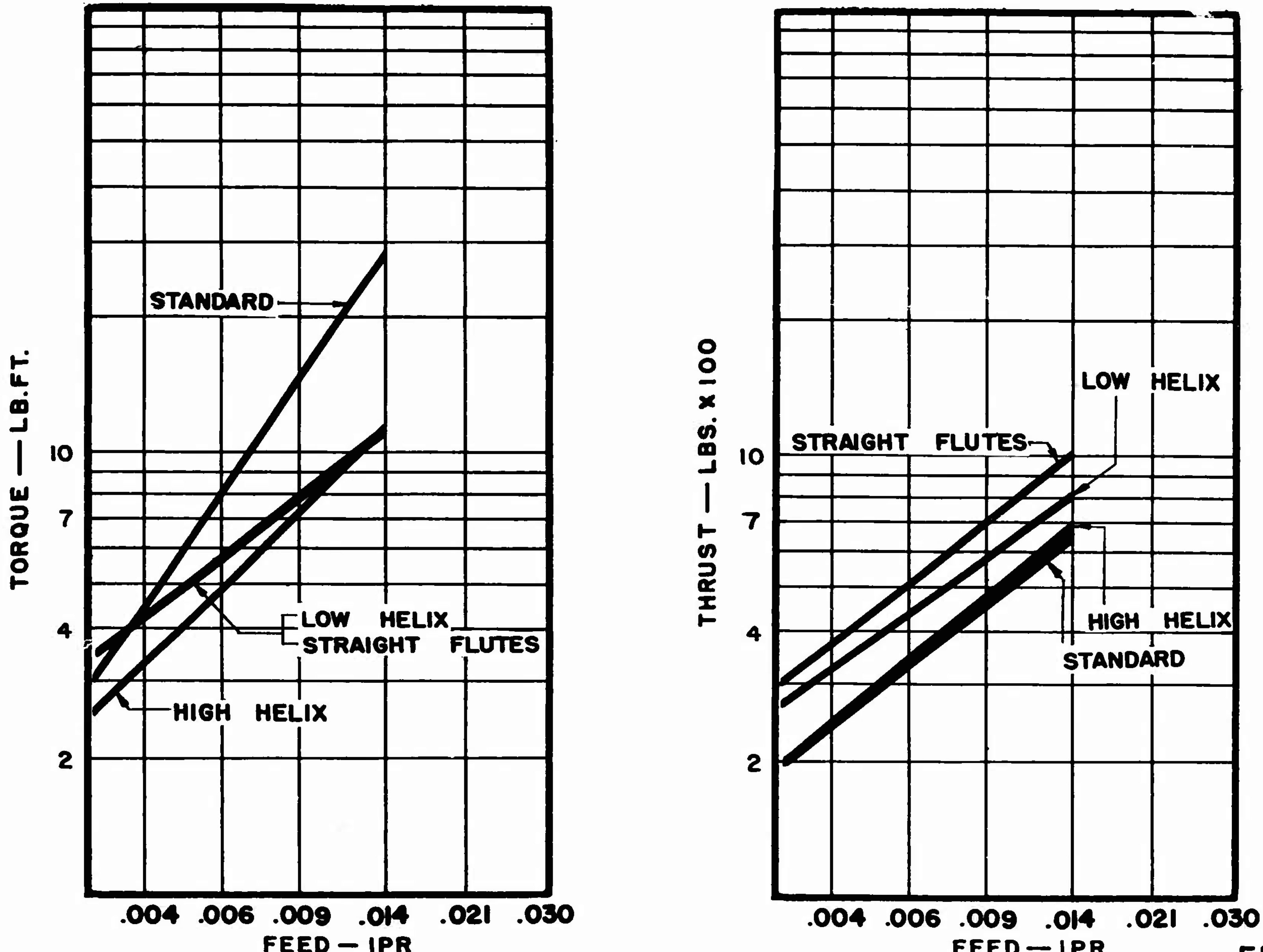


FIG. 23.

DRILLING TITANIUM

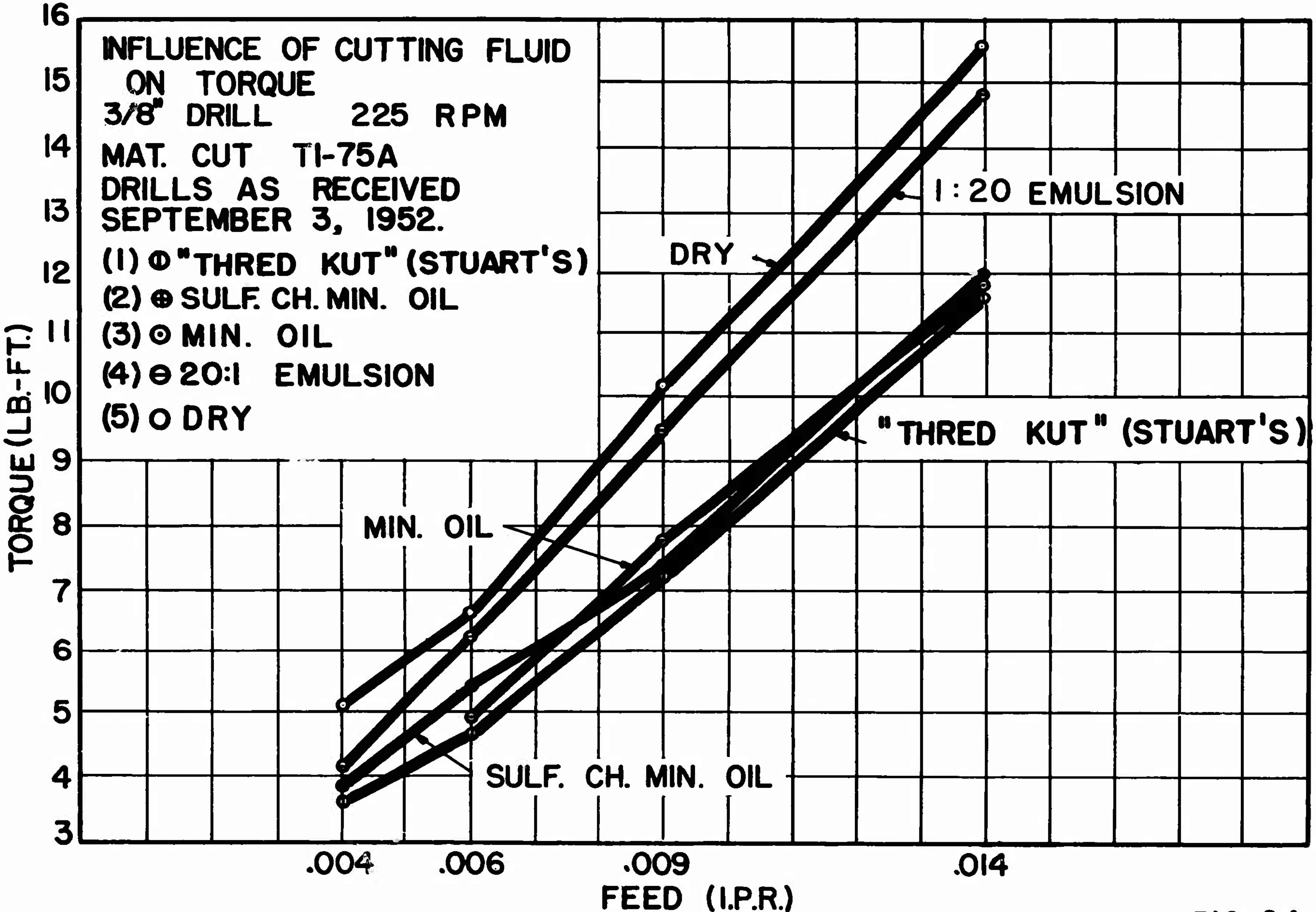


FIG. 24.

DRILLING TITANIAM

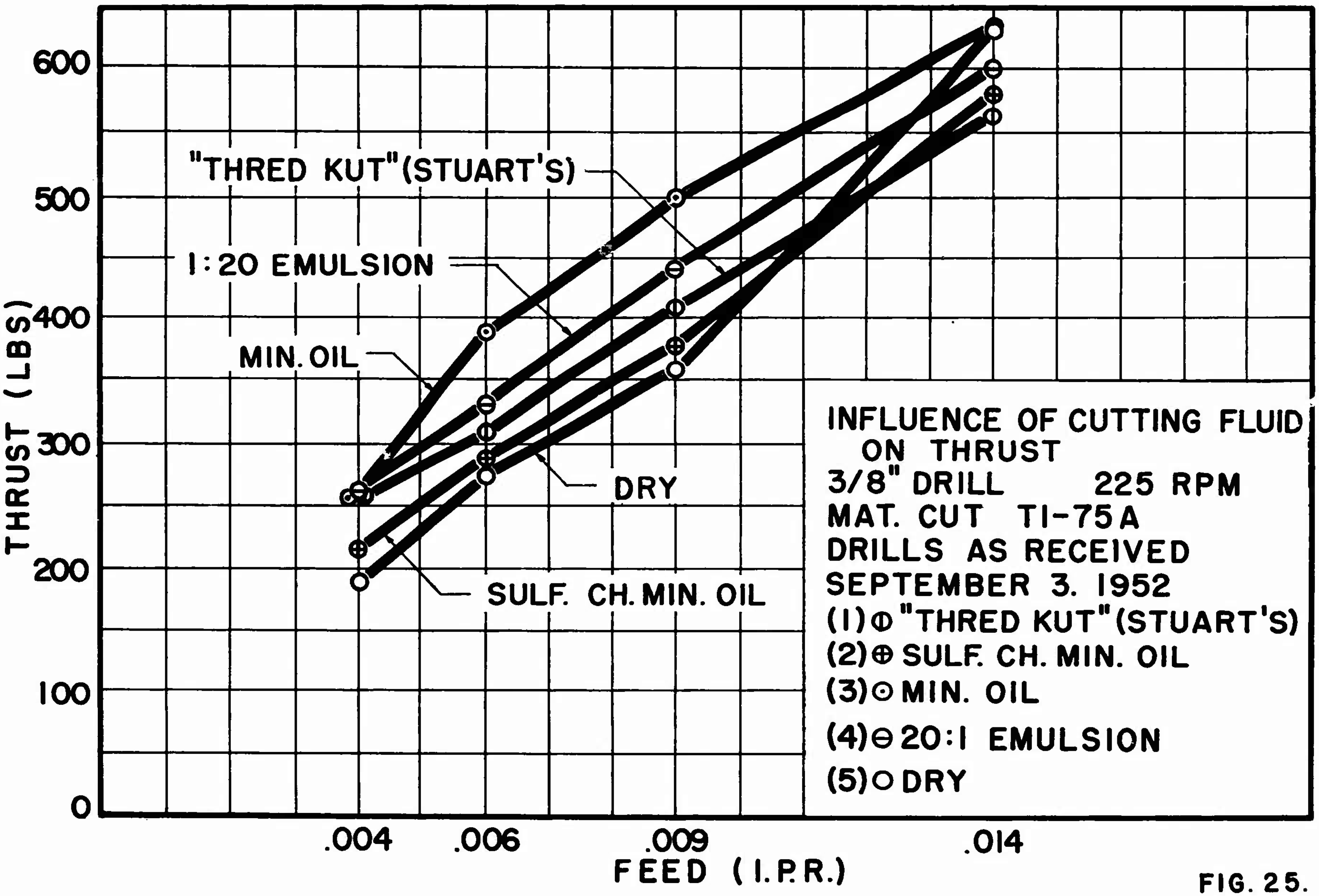


FIG. 25.

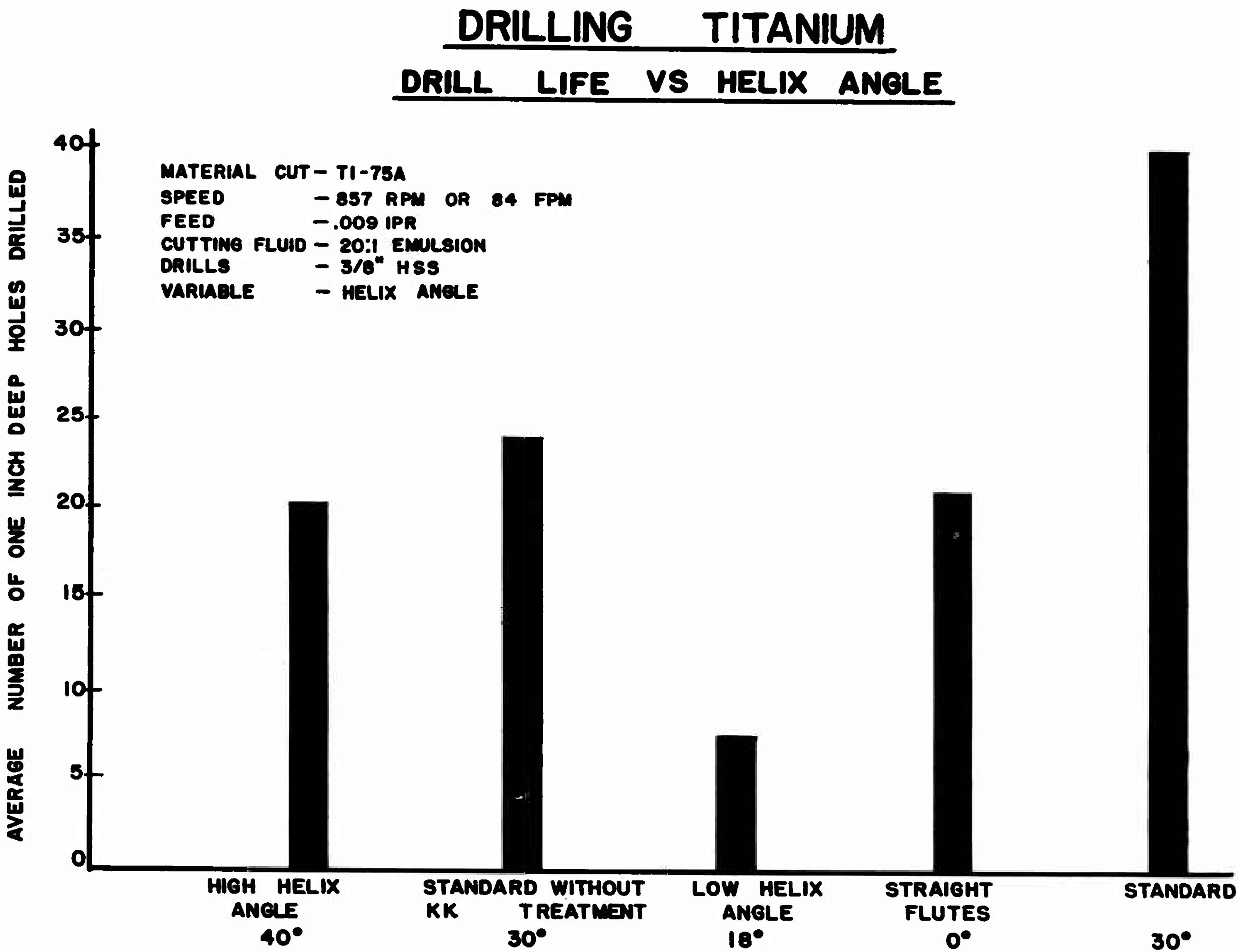

DRILLING TITANIUM
DRILL LIFE VS HELIX ANGLE
MATERIAL CUT – TI-75A
SPEED – 857 RPM OR 84 FPM
FEED – .009 IPR
CUTTING FLUID – 20:1 EMULSION
DRILLS – 3/8" HSS
VARIABLE – HELIX ANGLE
AVERAGE NUMBER OF ONE INCH DEEP HOLES DRILLED
0
5
10
15
20
25
30
35
40
HIGH HELIX ANGLE 40°
STANDARD WITHOUT KK TREATMENT 30°
LOW HELIX ANGLE 18°
STRAIGHT FLUTES 0°
STANDARD 30°

FIG. 26.

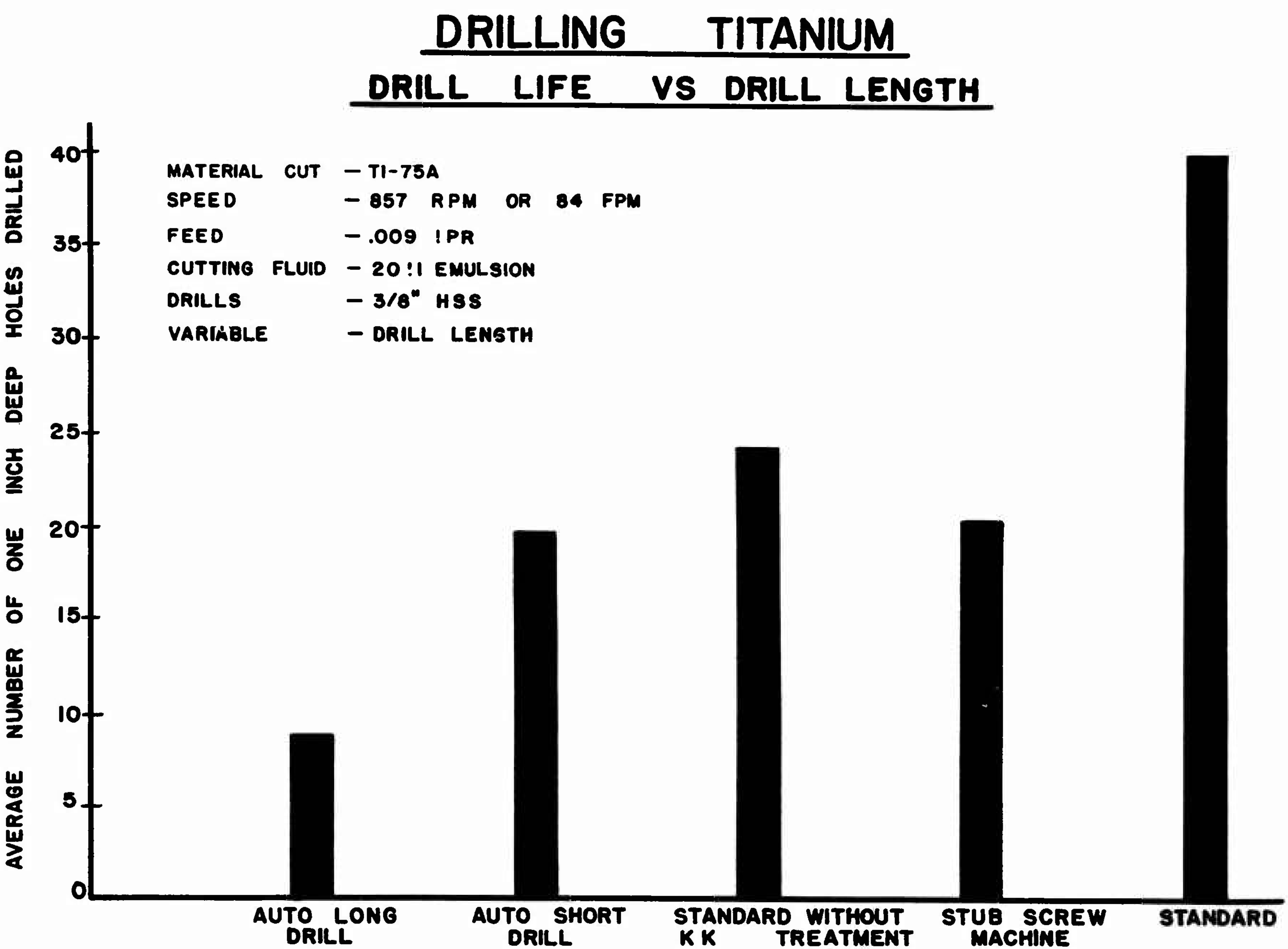

DRILLING TITANIUM
DRILL LIFE VS DRILL LENGTH
MATERIAL CUT — TI-75A
SPEED — 857 RPM OR 84 FPM
FEED — .009 IPR
CUTTING FLUID — 20:1 EMULSION
DRILLS — 3/8" HSS
VARIABLE — DRILL LENGTH
AVERAGE NUMBER OF ONE INCH DEEP HOLES DRILLED
0
5
10
15
20
25
30
35
40
AUTO LONG DRILL
AUTO SHORT DRILL
STANDARD WITHOUT KK TREATMENT
STUB SCREW MACHINE
STANDARD

FIG. 27.

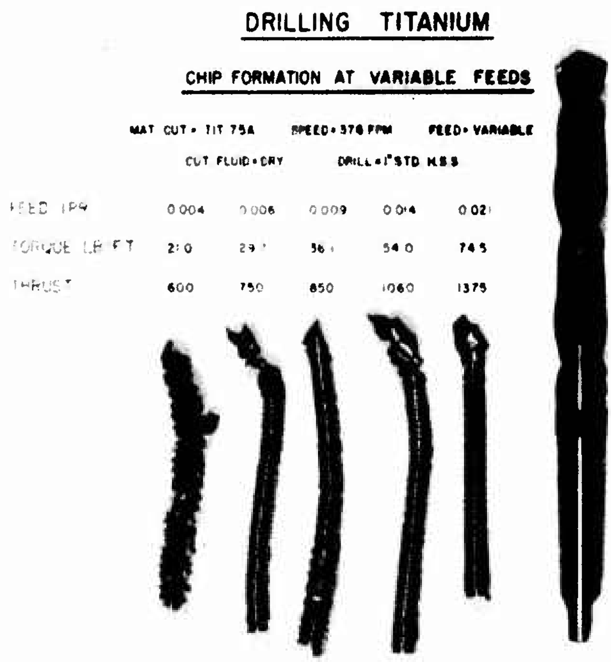

DRILLING TITANIUM
CHIP FORMATION AT VARIABLE FEEDS
MAT CUT = TIT 75A
FEED = VARIABLE
CUT FLUID = DRY
0.004 0.006 0.009 0.021
54.0
600 750 850 1060 1375

FIG. 28.

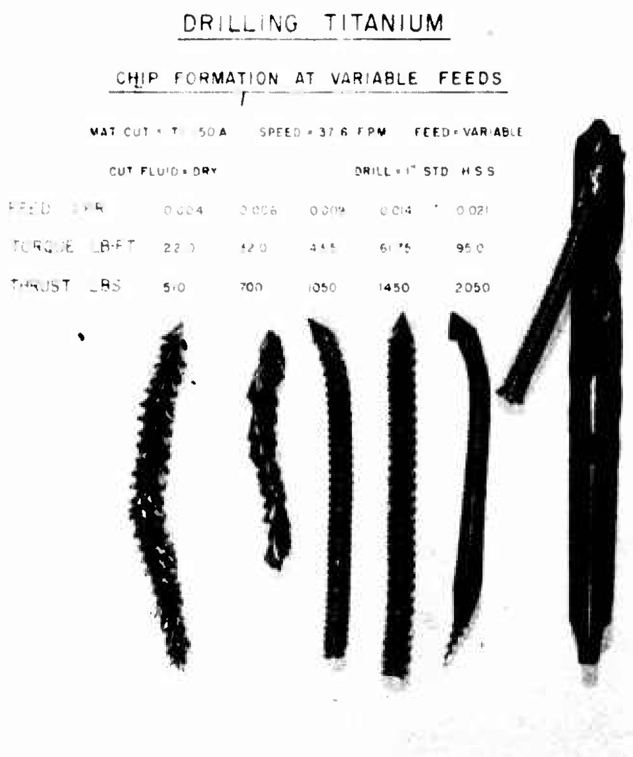

DRILLING TITANIUM
CHIP FORMATION AT VARIABLE FEEDS
FEED = VARIABLE
CUT FLUID = DRY
THRUST
700 1050 1450 2050

FIG. 29.

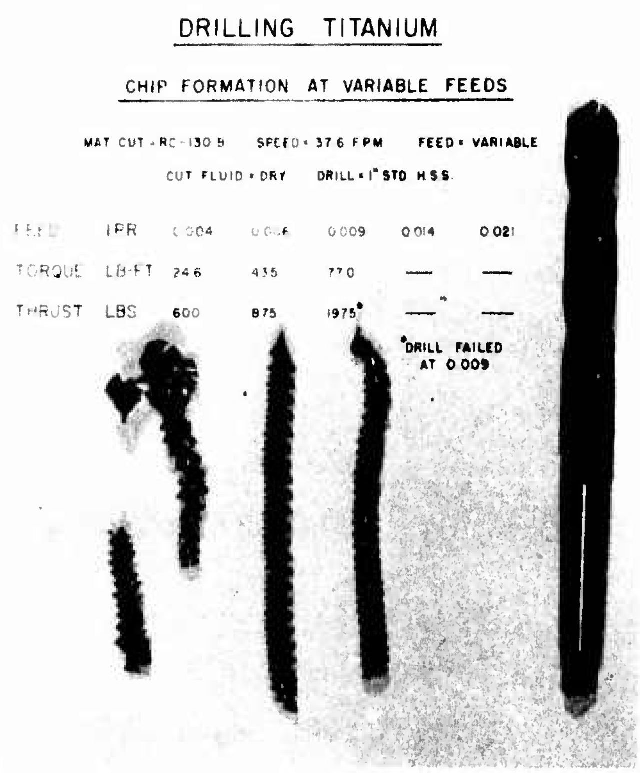

DRILLING TITANIUM
CHIP FORMATION AT VARIABLE FEEDS
MAT CUT - RC-130 B SPEED = 37.6 FPM FEED = VARIABLE
CUT FLUID = DRY DRILL = 1" STD H.S.S.
FEED IPR 0.004 0.006 0.009 0.014 0.021
TORQUE LB-FT 24.6 43.5 77.0 — —
THRUST LBS 600 875 1975* — —
*DRILL FAILED AT 0.009

FIG. 30.

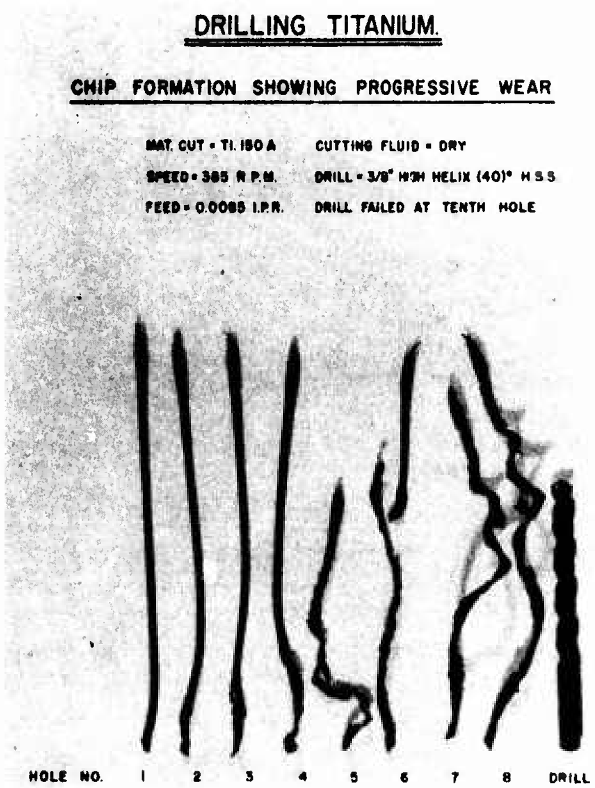

DRILLING TITANIUM.
CHIP FORMATION SHOWING PROGRESSIVE WEAR
MAT. CUT = TI. 150 A
CUTTING FLUID = DRY
SPEED = 385 R.P.M.
DRILL = 3/8" HIGH HELIX (40)° H.S.S.
FEED = 0.0085 I.P.R.
DRILL FAILED AT TENTH HOLE
HOLE NO. 1 2 3 4 5 6 7 8 DRILL

FIG. 31